Local cooling, global warming

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climate change and international policy strategies

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The interaction between local cooling demand,
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Proefschrift

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Michiel Hekkenberg

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If you want to go fast, go alone.
If you want to go far, go together.
(African Proverb)

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SUMMARY

This thesis investigates the interaction between local cooling demand and global warming and international policy strategies. The demand for local cooling, provided by refrigeration and air conditioning systems, is increasing in industrialized as well as developing countries. Because emissions of fluorinated refrigerants and emissions from the systems' energy consumption contribute to climate change, the expected continuation of this trend gives rise to climate policy concerns. Paradoxically, global warming itself may contribute to the increasing demand for local cooling.

The thesis is set against the background of the interaction between the two international environmental treaties that govern different fluorinated refrigerants: the Montreal Protocol to protect the ozone layer and the Kyoto Protocol to reduce global greenhouse gas emissions. Historically, cooling systems mainly used CFCs, which are currently phased out under the Montreal Protocol, because of their ozone depleting potential. This phase out has resulted in a transition towards using HFC refrigerants. Although this transition has successfully negated one environmental threat related to fluorinated refrigerants use, it has not (sufficiently) addressed their global warming potential. Therefore, the increasing use of fluorinated refrigerants remains an issue for environmental concern.

The first part of the thesis focuses on refrigerant emissions and related policies. It assesses qualitatively the interaction between policy instruments and characteristics of the individual (local) stakeholders and institutions that need to be involved for effective policy implementation. The qualitative assessments are supported by quantitative analyses of future refrigerant emissions in several countries in different policy scenarios. The second part of the thesis focuses on the temperature dependence of the energy demand from refrigeration and air conditioning.

The thesis' first assessment discusses the effect of global climate policy design on local stakeholder cooperation from a social dilemma perspective. It introduces and compares the Montreal Protocol and the Kyoto Protocol. This assessment argues that compared to ozone policy, global climate policy results in larger groups of stakeholders and higher uncertainty about optimal responses for individual stakeholders. It concludes that such design differences may help to explain the observed difference in policy effectiveness between ozone policy and climate policy. It suggests that future climate policy should

therefore better address the issues that affect stakeholder cooperation, for instance by setting sectoral or substance-based emission targets.

The thesis quantitatively assesses the environmental consequences of continuing business as usual regarding fluorinated refrigerant use in China, which serves as a model for rapidly developing countries. The assessment projects that the future refrigerant emissions from such countries may substantially contribute to the total greenhouse gas emissions at the global scale. It signals that the phase-out of ozone depleting substances under the Montreal Protocol significantly reduces the projected climate impact of refrigerant emissions. Next, it suggests that the exclusion of ozone depleting substances under the UNFCCC may cloud the accounting of refrigerant emissions in the context of climate change, which may result in suboptimal emission reduction strategies. The findings from this assessment underline the relevance of effectuating a successful policy strategy to reduce refrigerant emissions in developing countries.

A second quantitative assessment investigates the future environmental consequences of different policy strategies to reduce refrigerant emissions in Germany, which serves as a model for industrialized countries. Two principal emission reduction strategies are debated. The first strategy, “containment”, aims at reducing emissions by preventing leakages. It concerns mainly procedural rules that regulate operating and servicing of refrigeration and air conditioning systems. Such a strategy is presently adopted in the European Union for most refrigeration and air conditioning systems. The second strategy, “phase-out”, aims at reducing emissions by switching to different refrigerants or different refrigeration technologies altogether. It concerns mainly command and control regulation that prohibits the use of certain types of substances in certain applications. Such a strategy is adopted in the EU for mobile air conditioning. The assessment suggests that a containment strategy may be more effective in the short run than a phase-out strategy. However, it finds that such a phase-out strategy may be more effective in the long run, because it prevents stock build up and may thus prevent refrigerant emissions during use and during disposal of obsolete systems. The analysis suggests that a political preference for short term results and the economic discounting of future costs may result in an initial preference for a containment strategy, at the expense of more effective long term solutions.

The first parts’ final assessment puts the debate on different policy strategies to reduce the future refrigerant emissions in an integrative global perspective. It stresses the important role of acknowledging local variation when aiming for an effective global policy. This assessment investigates how the two main policy strategies, phase-out and containment, can be effectuated in developing countries. It assesses the expected effectiveness of several instruments that are currently being implemented or considered mainly in industrialized countries. The assessment suggests that each instrument may require a different level of institutional capacity and set requirements on different stakeholders in the governance system. The assessment concludes that a containment strategy may not be effective in developing countries, because it is aimed at individual local stakeholders (equipment users and service engineers) who may not have sufficient capacity to effectuate the policy. Additionally, local governments may not be able to set up the required institutions for enforcement and responsible refrigerant disposal. A phase-out strategy may be more successful, because it is principally aimed at different types of stakeholders (multinational refrigerant and equipment manufacturers) which

may be better capable to effectuate the policy. Moreover, these stakeholders are oriented at the international market and may therefore be influenced by market regulation in industrialized countries, even if they are based in developing countries. The development of alternative technologies for the industrialized countries' market may facilitate technology transfer towards developing countries.

The first part of the thesis uses a multidimensional and multidisciplinary analytical framework to investigate possible future policy strategies that effectively reduce fluorinated refrigerant emissions. It analyzes the triangular interaction between the socio-economical, the environmental and the policy system and investigates the spatial and temporal variation within this triangle. It suggests that the 'one-sided' adoption of emission reduction targets by industrialized countries has resulted in present policies to reduce refrigerant emissions that are mostly based on the local situation in industrialized countries. The thesis suggests that the local situation in developing countries may substantially deviate from that in industrialized countries, which may hamper developing countries in pursuing the refrigerant containment strategy selected in various industrialized countries. Given the need to reduce future refrigerant emissions from both industrialized countries as well as developing countries and the adoption of 'common but differentiated responsibilities' between developing countries and industrialized countries in global climate policy the thesis concludes:

> *because of the global interconnectedness of the socio-economic, physical and policy systems, an effective long term climate policy should aim at globally phasing-out high GWP refrigerant use, starting in industrialized countries.*

The second part of the thesis points out that energy demand from local cooling is temperature dependent. It studies the consequences of increasing use of local cooling systems for electricity and energy consumption both on a local and a global scale. It finds a changing temperature dependence pattern of total electricity consumption in the Netherlands and links this phenomenon to the increasing use of local cooling systems. It further discusses the consequences of such changing temperature dependence patterns for modeling energy demand in the context of climate change. It concludes:

> *the increasing use of refrigeration and air conditioning systems may change the temperature dependence pattern of electricity demand. Global energy demand models that address future energy demand in the context of climate change should accommodate such and other socio-economic developments by dynamically modeling the temperature dependence pattern.*

SAMENVATTING (SUMMARY IN DUTCH)

Dit proefschrift behandelt de relatie tussen de vraag naar koeling, klimaatverandering en het hieraan gerelateerde milieubeleid.

Inleiding

Koelsystemen worden op allerlei plaatsen in de maatschappij gebruikt. Zo is koeling onder andere nodig voor industriële productieprocessen en bij het verwerken, vervoeren en bewaren van voedsel. Airconditioning zorgt voor een aangename omgevingstemperatuur tijdens het werk, thuis of in de auto. Op al deze manieren verhogen koelsystemen het menselijk welzijn. Zowel op nationaal als op wereldwijd niveau is het gebruik van koeling en airconditioning de afgelopen decennia gestaag gegroeid. Men mag verwachten dat deze trend zich in de toekomst voortzet, door onder andere verdere economische ontwikkeling en het veranderende klimaat.

Het gebruik van koelsystemen heeft echter ook keerzijden. Koelsystemen belasten het milieu door het gebruik van energie en door het gebruik van gefluorideerde koelvloeistoffen (CFK's, HCFK's en HFK's). Het gebruik van energie leidt in het hedendaagse energiesysteem tot de uitstoot van het broeikasgas CO_2. Bovendien kan het toenemend gebruik van koelsystemen leiden tot veranderende lokale en wereldwijde energiegebruikspatronen, doordat het energiegebruik van koelsystemen afhankelijk is van de buitentemperatuur. Zulke veranderingen kunnen gevolgen hebben voor de voorzieningszekerheid van energie, die essentieel is voor het functioneren van grote delen van de maatschappij.

De meeste gefluorideerde koelvloeistoffen zijn zeer sterke broeikasgassen, tot duizenden malen sterker dan een zelfde gewicht aan CO_2. Wanneer deze stoffen door onzorgvuldig handelen, lekkage, of een ongeluk vrijkomen uit het koelsysteem dragen ze daarom net als CO_2 bij aan klimaatverandering. Het gebruik van koeling leidt dus, paradoxaal genoeg, tot opwarming van de aarde.

Klimaatonderzoek wijst op de noodzaak tot drastische vermindering van de wereldwijde uitstoot van broeikasgassen in de eerste helft van de 21^{e} eeuw om gevaarlijke klimaatverandering te voorkomen. Daarom is in de jaren '90 een begin gemaakt met internationale klimaatafspraken, onder andere in de VN Raamwerkafspraak over klimaatverandering (UNFCCC) van 1992, waaruit in 1997 het Kyoto Protocol voortkwam. Verdergaande afspraken zijn het onderwerp van voortdurende onderhandelingen.

Internationaal is afgesproken dat CFK's en HCFK's niet onder het klimaatbeleid vallen, omdat deze niet alleen bijdragen aan het broeikaseffect maar ook de ozonlaag aantasten. Als zodanig worden ze al via het Montreal Protocol (van 1987) uitgebannen; eerst in geïndustrialiseerde landen en later in ontwikkelingslanden. Dit ozonverdrag zorgt voor een verschuiving van het gebruik van CFK's en HCFK's naar de niet-ozonafbrekende HFK's en andere koelvloeistoffen. HFK's vallen wel onder het klimaatbeleid.

Ondanks de relatief beperkte bijdrage van gefluorideerde koelvloeistoffen aan de totale uitstoot van broeikasgassen (1-5% in 2004) is de uitstoot van HFK's voor enkele geïndustrialiseerde landen reden genoeg voor de ontwikkeling van gericht beleid. De toename van het gebruik van koelsystemen en de verschuiving in koelvloeistofgebruik leiden samen tot een sterke stijging van het gebruik en de uitstoot van HFK's wereldwijd, het sterkst in ontwikkelingslanden. Zowel door hun geringe bijdrage aan de wereldwijde uitstoot van broeikasgassen tot nu toe als door hun sterke gerichtheid op welvaartsverbetering, heeft beperking van de uitstoot in ontwikkelingslanden nog nauwelijks draagvlak. Wereldwijde beperking van de uitstoot van HFK's lijkt echter onmisbaar in een succesvolle lange termijn klimaatstrategie.

Doel

Dit proefschrift analyseert de beleidsmogelijkheden om in geïndustrialiseerde én ontwikkelingslanden de toekomstige uitstoot van HFK's uit koelsystemen te beperken. Het onderzoekt verder de gevolgen van het toenemende gebruik van koeling op energiegebruikspatronen.

Theoretisch kader

De analyses in deel één van dit proefschrift gebeuren vanuit een multidisciplinair en dynamisch systeemperspectief. Het proefschrift beschouwt drie verschillende systemen in het maatschappelijk speelveld en hun onderlinge relaties. Ten eerste het sociaal-economische systeem van gedrag, consumptie en productie: de samenleving. Ten tweede het natuurlijke milieusysteem, dat voor veel sociaal-economische processen de basis vormt en er tegelijk door wordt beïnvloed. En tenslotte het beleidssysteem, dat probeert de wisselwerking van processen binnen de samenleving en van samenleving met milieusysteem in goede banen te leiden. Door hun onderlinge verbondenheid hebben veranderingen in het ene systeem vaak gevolgen in een of beide andere systemen. Het uiteindelijke beoordelingskader in de analyses is steeds de algemene staat van het milieusysteem en in het bijzonder de hoeveelheid uitstoot van broeikasgassen uit koelsystemen.

Naast deze analyse van het lokale maatschappelijk speelveld gaat het proefschrift ook in op de wereldwijde variatie en verbondenheid tussen de beschreven systemen. Lokale sociaal-economische, beleids- en milieusystemen kunnen behoorlijk van elkaar verschillen. Evengoed bestaat tussen deze systemen naast de lokale ook een wereldwijde wisselwerking; niet alleen in het klimaatsysteem, maar ook steeds meer in sociaal-economische en beleidssystemen. Ontwikkelingen met gevolgen voor uitstoot van broeikasgassen in één lokaal systeem hebben daardoor automatisch gevolgen voor lokale systemen elders ter wereld. Lokale samenlevingen ondervinden door wereldwijde handel en internationale beleidsmaatregelen steeds meer invloed van buitenaf. Tegelijk zorgt lokale variatie mogelijk voor een verschillend lokaal probleembesef en verschillen in de mogelijkheden om (globale) problemen aan te pakken. Het proefschrift onderzoekt hoe zulke lokale variatie de mogelijkheden voor een wereldwijde beperking van de uitstoot van schadelijke koelvloeistoffen beïnvloedt.

Deel twee van het proefschrift gaat in op het energiegebruik van koeling en airconditioning. De energievraag van koeling is temperatuursafhankelijk: bij hogere buitentemperaturen gebruiken koelsystemen meer energie en is er ook meer vraag naar koeling en airconditioning. De energievraag van verwarming is juist omgekeerd temperatuursafhankelijk. Onder andere hierdoor wisselt de energievraag gedurende de seizoenen. Door zijn temperatuursafhankelijkheid kan het toenemende gebruik van koeling de verhouding van energiegebruik in de winter en de zomer beïnvloeden. Dit kan belangrijk zijn voor de planning van de energieproductie.

Bovendien leidt de opwarming van de aarde door klimaatverandering tot extra energiegebruik voor koeling en tot verminderd energiegebruik voor verwarming. Het totale effect hiervan in een land is afhankelijk van de balans tussen deze twee tegengestelde effecten en verschilt met de geografische positie en de sociaal-economische structuur. Veel ontwikkelingslanden liggen in warmere klimaatzones dan veel geïndustrialiseerde landen. Een snellere economische ontwikkeling in ontwikkelingslanden dan in geïndustrialiseerde landen leidt door de temperatuursafhankelijkheid mogelijk tot extra verandering in wereldwijde energiegebruikspatronen. In deel twee van het proefschrift staat daarom de vraag centraal hoe het energiegebruik door koelsystemen de huidige en toekomstige energievraagpatronen beïnvloedt.

Methode

Het proefschrift analyseert de gevolgen van bepaalde ontwikkelingen of beleidsalternatieven op het gebied van koelvloeistofgebruik aan de hand van kwantitatieve jaargangmodellen en kwalitatieve beleidsanalyse.

Met een jaargangenmodel wordt berekend hoeveel koelvloeistof ieder jaar nodig is voor toepassing in nieuwe systemen en voor bijvulling van weggelekte koelvloeistof, en hoeveel er ieder jaar via afgedankte systemen in het milieu verdwijnt. Echter, het inschatten van de effectiviteit van bepaalde beleidsmaatregelen vereist ook een goed begrip van de sociale of economische werkingsmechanismen binnen het sociaal-economisch systeem. De analyses in het proefschrift maken daarom gebruik van inzichten uit zowel de exacte als uit de sociale wetenschappen. Het proefschrift bestaat uit een aantal deelstudies, die vanuit een verschillend perspectief een deel van de beschreven systemen analyseren. Samenvoeging van de inzichten uit deze deelstudies leidt tot een robuuste conclusie over de beleidsmogelijkheden om de uitstoot van HFK's te beperken.

Bevindingen

Een tweetal deelstudies in dit proefschrift beschrijft kwantitatief de verwachte uitstoot van HFK emissies. Hoofdstuk 3 berekent de tot 2030 verwachte uitstoot van koelvloeistoffen in China, en geeft zo een beeld van de gevolgen van de verwachte snelle economische groei in sommige grote ontwikkelingslanden. In deze landen speelt de overgang van CFK's en HCFK's naar HFK's in genoemde periode een belangrijke rol. Het blijkt dat de uitstoot van koelvloeistoffen in China kan oplopen tot 0,5-1 gigaton CO_2-equivalent per jaar. Dit is gelijk aan 1-2% van de totale wereldwijde uitstoot van broeikasgassen in 2004. Een dergelijke ontwikkeling maakt het halen van noodzakelijke klimaatdoelen erg moeilijk, zeker wanneer koeling in andere grote ontwikkelingslanden zoals India een zelfde uitstoot gaat veroorzaken.

Hoofdstuk 4 analyseert de effecten van mogelijk beleidsingrijpen op de uitstoot van HFK's in Duitsland. Vanwege de lange levensduur van koelsystemen blijkt een beleid dat het gebruik van HFK-koelsystemen inperkt, op korte termijn mogelijk minder effectief te zijn dan een beleid dat zich richt op het verminderen van de uitstoot van HFK's door een zorgvuldiger omgang met de systemen. Echter op lange termijn is inperken van de HFK-koelsystemen mogelijk juist effectiever, doordat er dan na verloop van tijd steeds minder HFK-systemen gebruikt worden. Bovendien kan een vroegtijdige omschakeling naar alternatieve koelsystemen, vóórdat er een grote hoeveelheid HFK-systemen in omloop is, de cumulatieve uitstoot over de jaren belangrijk verminderen. Deze bevinding is met vooral van belang in ontwikkelingslanden, waar nu nog beperkte hoeveelheden HFK-systemen gebruikt worden.

Een tweetal kwalitatieve analyses gaat in op de verschillende eigenschappen van beleid en van de daarbij betrokken actoren. Hoofdstuk 2 vergelijkt het beleid in het Montreal Protocol met dat in het Kyoto Protocol. De studie constateert dat de opzet van het Kyoto Protocol leidt tot een grotere groep actoren die samen verantwoordelijk zijn voor het bereiken van het beleidsdoel. Ook veroorzaakt deze opzet bij actoren een grotere onzekerheid over hun eigen optimale manier van handelen en over het handelen van andere actoren. Deze situatie kan er volgens sociaal-wetenschappelijke studies toe leiden dat actoren vaker kiezen voor eigen gewin dan voor een alternatief dat leidt tot een collectief optimum. De lagere effectiviteit van het Kyoto Protocol ten opzichte van het Montreal Protocol wordt hier in deze studie mee in verband gebracht. Het hoofdstuk suggereert op basis van deze bevindingen dat een toekomstig internationaal klimaatbeleid kan worden versterkt door de groepsgrootte van betrokken actoren te verkleinen en onzekerheden weg te nemen. Dit kan bijvoorbeeld door doelen per sector of per type broeikasgas (zoals HFK's) te stellen in plaats van één allesomvattend doel.

Hoofdstuk 5 onderzoekt de effectiviteit van verschillende beleidsinstrumenten om de wereldwijde uitstoot van HFK's terug te dringen. Vooral bij de mogelijkheid tot het verminderen van de uitstoot in ontwikkelingslanden worden nu veel vraagtekens geplaatst. Dit onderzoek gaat in op de verschillen tussen de actoren die betrokken zijn bij de verschillende sociaal-economische processen in de zogenaamde productketen van koelsystemen: productie van koelvloeistof, productie van koelsystemen, installatie, gebruik, onderhoud en afdanking. Ieder van deze actoren heeft invloed op de uiteindelijke HFK-uitstoot van het koelsysteem. De vraag is dus op welke actoren het beleid zich het beste kan richten. Bovendien gaat dit onderzoek in op de verschillen tussen ontwikkelingslanden en geïndustrialiseerde landen, wat betreft actoren en het beleidssysteem. Deze verschillen leiden ertoe dat bepaalde beleidsinstrumenten in sommige situaties wel en in andere minder effectief zijn. Het onderzoek concludeert dat het huidige EU-beleid rond koelvloeistoffen in ontwikkelingslanden niet tot effectieve navolging zal leiden. Dat beleid richt zich nu op het beperken van de uitstoot door een zorgvuldiger omgang met koelsystemen door installatie- en onderhoudsmonteurs. Het vereist bepaalde prioriteiten bij de bevolking en overheid, een behoorlijk opleidingsniveau van de betrokken actoren, en voldoende institutionele capaciteit om het beleid uit te voeren. Al deze randvoorwaarden zijn waarschijnlijk onvoldoende aanwezig in ontwikkelingslanden en ze kunnen daar ook amper vanuit geïndustrialiseerde landen worden opgebouwd. Het onderzoek stelt dat als het Europese beleid zich zou richten op het uitbannen van HFK's door technologieverandering er betere kansen zouden zijn. Immers zo'n beleid richt zich op andere actoren (vaak internationaal opererende bedrijven) die dat beleid wellicht beter kunnen uitvoeren. Europees beleid kan internationaal opererende bedrijven aanzetten tot technologieverandering om toegang tot de Europese markt te behouden, waarna de technologie overal ter wereld gebruikt kan worden. Bovendien kunnen de hierbij betrokken actoren gemakkelijker (via financiële mechanismen) geholpen worden vanuit de geïndustrialiseerde landen om eventuele extra kosten door het gebruik van nieuwe technologie in ontwikkelingslanden te compenseren.

De studies in deel twee richten zich op energiegebruikspatronen. Hoofdstuk 6 onderzoekt of het toegenomen gebruik van koelsystemen een mogelijke verschuiving heeft veroorzaakt in het elektriciteitsverbruikspatroon in Nederland. Door voor de periode 1970-2007 het dagelijkse elektriciteitsverbruik te vergelijken met de dagelijkse gemiddelde buitentemperatuur is voor iedere maand in deze periode de temperatuursafhankelijkheid bepaald. Het blijkt dat de temperatuursafhankelijkheid van elektriciteitsverbruik vroeger in alle maanden negatief was. Dat wil zeggen dat voor iedere maand over het algemeen gold: hoe hoger de temperatuur, hoe lager het elektriciteitsverbruik. Echter, in de zomermaanden treedt in de loop der tijd een kentering op en wordt voor recentere jaren een duidelijk positieve temperatuursafhankelijkheid gevonden. Voor de maanden mei tot en met september geldt tegenwoordig meestal dat een hogere temperatuur leidt tot een hoger elektriciteitsverbruik. De studie suggereert dat een toegenomen gebruik van koeling mogelijke geleid heeft tot deze verschuiving.

Hoofdstuk 7 gaat verder in op de temperatuursafhankelijkheid van energiegebruik. Verschillende studies blijken de gevolgen van klimaatverandering voor het toekomstige energiegebruik te analyseren. Ze houden echter vaak geen rekening met de veranderingen in de temperatuursafhankelijkheid door sociaal-economische ontwikkelingen, terwijl die op de langere tijdsschaal die past bij klimaatverandering wel degelijk kunnen optreden. De studie concludeert dat dit kan leiden tot een onderschatting van het toekomstige wereldwijde energiegebruik en doet daarom enkele suggesties voor verbetering van de gebruikte modellen.

Conclusie

Dit proefschrift plaatst het terugdringen van de uitstoot van HFK's nadrukkelijk binnen het kader van een wereldwijd en lange termijn klimaatbeleid. Tegelijkertijd wordt die uitstoot ook gezien als het gevolg van lokale processen onder allerlei omstandigheden, waarbij verschillende typen actoren betrokken zijn. Het proefschrift concludeert dat door deze lokale variatie en verschillen tussen de actoren alleen een beleid gericht op het uitbannen van HFK's door technologieverandering uiteindelijk zal leiden tot een effectieve wereldwijde beperking van de uitstoot. Het beleid in geïndustrialiseerde landen moet zich daarom richten op technologieverandering zodat de nodige technologieën ook in ontwikkelingslanden gebruikt kunnen worden.

Het proefschrift concludeert verder dat het toenemende gebruik van koeling de temperatuursafhankelijkheid van het elektriciteitsverbruik kan veranderen en dat energiemodellen die de verandering van het toekomstig energiegebruik onder invloed van klimaatverandering analyseren hier nu nog te weinig rekening mee houden.

1. INTRODUCTION

1.1. General introduction: societal development and environmental pressure

One of the main driving forces for societal development is mankind's perpetual aim to improve personal living and working conditions. Most developments throughout history, such as the development of tools, techniques, applications, machinery, procedures and institutions may be considered to target either the effectiveness or the efficiency of mankind's control over its surroundings. In accordance with Maslow's theory of hierarchical needs [Maslow, 1943], early societal developments aimed mainly at (better) meeting basic 'subsistence' needs and later developments subsequently aimed at meeting more advanced human needs.

Refrigeration and air conditioning systems, an overarching theme in the thesis, form a clear and one of the most literal examples of the realization of such human control over the local environment. The discussion of refrigeration and air conditioning systems throughout the thesis can therefore provide an illustration for societal developments in general. A coincidental parallel between general societal development and the development of refrigeration and air conditioning systems exists in the functional shift observed in the latter from providing basic human needs (food security) to providing more advanced needs (comfortable ambiance).

The effort to control the living and working environment often involves active intervention in the natural environment, which in turn may have unintended consequences. Resource use and resource depletion, land use change and harmful emissions interfere with the natural life support systems. Still, natural systems are generally resilient and can cope with or adapt to certain levels of disturbance. However, the continuous expansion of the socio-economic system, resulting from the combination of the continuous development (and consumption) of ever more services and an increasing world population leads to continuously increasing environmental pressure. When induced pressures exceed the carrying capacity of the natural system, the resulting environmental degradation may lead to eroding life-support functions and services provided by natural systems.

Environmental degradation can occur at various spatial and temporal scales. Historically, local environmental pressures led to mainly local excesses of the natural carrying capacity and resulted in localized and relatively direct environmental degradation. Examples of such local pressures are waste-dumps leading to malodor and water pollution, deforestation leading to local soil erosion and factories leading to noise. As populations grew and the socio-economic system developed further, the environmental effects of socio-economic activity at more spatially distant scale became visible, such as the culmination and distribution of waste emissions through water and air leading to pollution of downstream water sources and acid rain. In parallel, other activities resulted in eroded carrying capacity of natural systems at a more temporally distant scale, such as the depletion of fish stocks due to continuous overfishing and the bio-magnification of dichlorodiphenyltrichloroethane (DDT) along the food-chain.

At present, the expansion of our socio-economic system has reached the level at which its environmental impact is noticeable at the global scale. Such global impacts are not only simply the result of local impacts being created on a very widespread spatial scale; mankind’s activities are also influencing certain global environmental systems on a scale which is to significantly alter the balance in these systems. This cumulative influence of human activities on the global natural system is currently even conceived to be so large that geologists are debating whether it may have moved the planet earth into a new geological era dubbed the ‘anthropocene’ [Crutzen, 2002].

Anthropogenic emission of ozone depleting substances has partially depleted the stratospheric ozone layer, which essentially forms a protective layer guarding terrestrial life from potentially lethal ultra violet radiation. Excess emission of greenhouse gases leads to increased radiative forcing which will lead to an increased average global temperature. The resulting climatic change is expected to potentially lead to, amongst others, ecosystem loss, sea level rise, increasing frequencies of extreme weather events and subconsequent decreasing crop yields, economic damage and increased threats to all living organisms. As is illustrated in the next section, the use of refrigeration and air conditioning systems to provide local cooling contributes to both of these global environmental system disturbances.

1.2. Environmental pressure from refrigeration and air conditioning

Refrigeration and air conditioning (R+AC) form illustrative examples of socio-economic activities in general, as described in section 1.1. R+AC systems serve widely varying functions.

The development of refrigeration systems has substantially contributed to improved food conservation and safety, both industrially and domestically. E.g. refrigerated processing and conservation of food products has made humans less dependent on unfavorable conservation techniques such as salting and smoking; has enabled wider distribution of locally produced products, opening up distant markets; has enabled concentration of food processing activities leading to economies of scale and has reduced the required frequency for grocery shopping, enabling more convenient living patterns. Moreover, the development of refrigeration has been crucial for cooling various industrial processes, drug conservation, and many others. The development of air conditioning systems has enabled people to live, work and drive more comfortably in warm and humid climates. Although such added comfort may be regarded a luxury in various circumstances, events such as the heat wave in the summer of 2003 and its related excess mortality (eg [Fouillet et al., 2006]) show human vulnerability to extreme climates. Moreover, air conditioning can improve attention during driving, thereby possibly reducing road accidents and can increase work efficiency and thus productivity.

Thus, refrigeration and air conditioning (R+AC) systems have clearly contributed positively to societal development. However, current R+AC systems also lead to important pressures on the environment. Most current R+AC systems use similar technological mechanisms, in which a vapor-compression cycle is used to transport heat out of a controlled (cooled) space by means of a circulating refrigerant. Of the refrigerants currently used in these systems 96% are synthetic fluorinated gases [IPCC and TEAP, 2005 Table TS-11], which, if released into the atmosphere, may contribute substantially to ozone depletion and climate change. Similar substances are used as foam blowing agents in insulating foams. Moreover, operating R+AC systems requires energy and thus, in the current energy system, leads to additional greenhouse gas (GHG) emissions. Furthermore, the temperature dependence of R+AC system energy demand may have important consequences for energy planning strategies.

Because the global use of R+AC systems is expected to increase, so is their expected cumulative impact on the environment and energy demand. The thesis investigates these impacts related to the use of R+AC systems and policy approaches to mitigate them. It focuses on vapor-compression systems using fluorinated refrigerants and more specifically on these systems' contribution to climate change, and their consequences for energy demand. This section underpins this choice by further clarifying the environmental and energy impacts of R+AC systems and their significance for future policy strategies.

1.2.1. Ozone depletion

Many people's prime association of environmental pressure related to R+AC systems is the depletion of the stratospheric ozone layer. The theoretical description of ozone depletion induced by chlorine radicals generated from the degradation of chlorofluorocarbons (CFCs) by ultraviolet radiation in the stratosphere [Molina and Rowland, 1974] and the subsequent discovery of the Antarctic 'ozone-hole', led to an international agreement to reduce the production and use of ozone depleting substances (ODSs) in the Montreal Protocol [UN, 1987]. The original Montreal Protocol restricted mainly the use of CFCs in various applications, such as refrigerants and foam blowing agents in R+AC systems.

Multiple replacement options for CFCs existed in R+AC systems, in the form of hydrochlorofluorocarbons (HCFCs), Hydrofluorocarbons (HFCs) and so-called 'natural' substances: a mixed group of ammonia (NH_3), hydrocarbons (HCs) and carbon dioxide (CO_2). HCFCs generally have a lower Ozone Depleting Potential (ODP[1]) than CFCs and both HFCs and natural substances are not ozone depleting at all. Soon after its original ratification though, an improved understanding of the relation between ODS emissions and ozone depletion suggested the original protocol was not sufficient to protect the ozone layer. Six subsequent amendments (1990, 1992, 1995, 1997, 1999 and 2007) led to a stepwise phasing-out of the use and production of most ODSs including HCFCs. All versions of the Montreal Protocol have differentiated time schedules for phase-outs, always starting with a phase-out in industrialized countries and followed later by one in

[1] ODP is used as a measure of ozone depleting potential of a substance relative to CFC-11

developing countries. Although the ODSs emitted thus far will continue to exert their effects for a long time into the future, the drastic cut in their projected future emission is expected to result in a restoration of the ozone layer to 1980 levels around the middle of the 21st century [Bodeker and Waugh, 2006]. Since no feasible physical options exist to speed up this process, the remaining challenge regarding ozone depletion is to control the stocks of ODS in already existing applications to prevent further 'chlorine loading' of the atmosphere that would delay ozone layer restoration. Therefore in the thesis, the ozone depleting consequences of R+AC systems are not specifically addressed.

1.2.2. Climate change

Instead, the thesis focuses on the contribution of R+AC systems to greenhouse gas emissions. Anthropogenic GHG emissions strengthen the natural greenhouse effect and thereby lead to increasing global average temperatures (global warming), resulting in climate change. Climate change has various consequences for the environment, which, as noted before, may have severe societal consequences. The United Nations Framework Convention on Climate Change (UNFCCC), signed by 192 nations globally thus far [UNFCCC, 2009b], addresses such dangerous anthropogenic interference in the climate system. Specifically, the stated goal of the UNFCCC is to *"achieve stabilization of greenhouse gas concentrations in the atmosphere at a low enough level to prevent dangerous anthropogenic interference with the climate system"* [UN, 1992b]. UNFCCC lists six (groups of) greenhouse gases that contribute to climate change: CO_2, CH_4, N_2O, HFCs, PFCs and SF_6. Although CFCs and HCFCs are also highly potent GHGs, they are not listed by UNFCCC because they are already controlled under the Montreal Protocol.

As noted above, UNFCCC aims to prevent dangerous interference with the climate system. IPCC [2007] has related the extent of expected damage in several damage categories to average global temperature increase above pre-industrial (1850) levels. The IPCC report and recent updates [Smith et al., 2009] show that a global temperature increase of more than 2ºC may lead to critical damage in various effect categories or "reasons for concern". Limiting global temperature increase to 2ºC is therefore thought to be required to prevent the stated dangerous interference with the climate system.

IPCC [Gupta and Tirpak, 2007] shows that limiting average warming to 2ºC requires drastic reductions of global GHG emissions. In industrialized countries, emission reductions of 40-90% compared to 1990 emissions are needed by 2050 and even further reductions towards 2100, in order not to exceed the estimated atmospheric GHG concentration threshold of 550 ppm (measured in CO_2-equivalents). Even with this effort, the 2ºC target is highly likely to be overshot [Meinshausen, 2005]. R+AC systems contribute to GHG emissions both by their emission of fluorinated gases and by the emissions related to their (fossil fuel based) energy use. Ironically, since global warming may be expected to lead to increased cooling demand and increasing use of R+AC systems leads to increasing GHG emissions and subsequent additional warming, local cooling and global warming currently form a mutually enforcing positive feedback loop.

1.2.3. Fluorinated gases

Current emissions

As noted above, fluorinated gases are used as refrigerants and foam blowing agents in e.g. insulating foams. Fluorinated gases (F-gases) generally have high global warming potential (GWP[2]), as shown in Table 1. The physico-chemical properties of F-gases make them highly efficient heat-transporters in vapor-compression cycles in R+AC systems. Combined with their general low toxicity and low flammability, F-gases are the refrigerant of choice in many R+AC systems. Moreover, the insulating and fire-resistant properties of F-gases make them very useful as foam blowing agents.

Alternatively, systems may use so-called 'natural refrigerants' such as ammonia, propane, butane or carbon dioxide, which are not ozone depleting and have low if any global warming potential. R+AC systems may also apply 'not-in-kind' technologies, which provide heat transport through altogether different technologies such as the Stirling cycle, absorption cycle, thermoelectric cooling, thermoacoustic cooling, magnetic cooling and trans-critical CO2 [UNEP, 2007a]. However, the use of such alternative refrigerants and technologies is currently limited, and is sometimes considered problematic due to concerns of toxicity or flammability of involved refrigerants, relatively low energy-efficiency of some technologies and high investment costs of developing and switching to alternative systems.

Refrigeration and air conditioning systems cause substantial emissions of refrigerants throughout their life cycle, especially during their use and disposal phases. Average emission rates of refrigerants from R+AC systems have been reported to be as high as 10-35% of the original charge per year for various types of applications [IPCC and TEAP, 2005]. These substantial leakage rates are partly due to the prevailing maintenance practices. When, due to leakage or disruptions, refrigerant charge drops below a critical charge, the system's heat transport effectiveness will be reduced. Thus, in order to maintain its effectiveness, the system needs to be repaired and its refrigerant charge refilled. Until recently, the common maintenance practice in most countries around the

Table 1.1 GWPs for 100yr time horizon for a selection of F-gases (from: [IPCC, 2007]).

Substances controlled by the Montreal protocol (CFCs and HCFCs)	GWP 100-yr	Hydrofluorocarbons (HFCs)	GWP 100-yr
CFC-11	4750	HFC-23	14800
CFC-12	10900	HFC-32	675
HCFC-22	1810	HFC-125	3500
HCFC-123	77	HFC-134a	1430
HCFC-142b	2310	HFC-143a	4470
		HFC-152a	124

[2] GWP is a measure of warming potential of substances compared to CO_2 integrated over a certain time period (generally 100 years).

world was to 'vent' the system's refrigerant out of the system, repair it, and replace the refrigerant by a full new charge. The refrigerant still remaining in the system was simply emitted into the air. Similarly, without responsible disposal, the charge remaining at the end of a system's functional life is also emitted. Throughout a system's lifetime, the total amount of refrigerant emitted would therefore be several times the original charge. More recently, increased environmental awareness in some industrialized countries has led to legislation that outlaws such practices and requires capturing a system's remaining charge and adequately disposing of it (eg. [European Commission, 2006b]). Such practice is expected to reduce emission significantly, although it is not expected to fully prevent emissions.

Emission rates from foams are generally much lower. Part of the foam blowing agents is emitted at foam manufacturing, the rest is emitted slowly (in closed cell foams) or quickly (in open cell foams) during the foams' lifetime. Blowing agent loss is not restored during the foams' lifetime. Prevention of emission during the foams' lifetime is not practically feasible, although the blowing agent remaining at the end of life can be collected and destroyed. Thus, blowing agent emissions are relatively straightforwardly dependent on production and disposal practices; users of foams have negligible influence on foam emissions. Responsible end of life disposal of foams contained in obsolete systems is lacking in many countries, just as disposal of refrigerants. Although improving responsible disposal of foams can make an important contribution to reducing F-gas emissions, the thesis focuses on refrigerant emissions, which are more important in volume and more complex due to a larger number of stakeholders that can actively influence emissions.

Emission of refrigerants during use and at disposal make an important contribution to the total global greenhouse gas emissions. IPCC and TEAP [2005] estimate 2002 refrigerant emissions from R+AC systems to equal 2Gt CO_2-equivalent; global CO_2 emissions are estimated to equal 29Gt [IPCC, 2007]. Detailed data on emissions of F-gases from R+AC systems is scarce, due to a lacking registration and monitoring; a reliable estimation of their combined current and future contribution to global warming is therefore difficult. In many discussions and documents, emissions of HFCs, PFCs and SF_6 from various applications are aggregated, which obscures the contributions from distinct applications. Moreover, because CFCs and HCFCs are not included in the UNFCCC and Kyoto Protocol, their emissions are often neglected in climate change studies and climate policy. This obscures the total contribution of fluorinated refrigerant emissions to the global climate change.

The 2005 IPCC/TEAP Special Report on Safeguarding the Ozone Layer and the Global Climate System [IPCC and TEAP, 2005] forms the most comprehensive collection of issues related to F-gas use and emissions. Its findings indicate that refrigerant emissions currently account for roughly 1% (excluding ODSs) or 5% (including ODSs) of global GHG emissions, which are estimated at 49Gt CO_2-equivalent in 2004 [IPCC, 2007]. It further finds that F-gas use and emission may be expected to increase rapidly in the future, as will be discussed below.

Clearly, such increase in emissions is hardly reconcilable with the drastic reductions required to prevent dangerous climate change. A large part of the thesis deals with the opportunities to counter the projected increase of emissions of fluorinated refrigerants as part of a successful climate policy.

Projected development

Because CFCs and HCFCs are controlled under the Montreal Protocol, HFCs are currently widely used as substitutes for these controlled substances, both in new systems and as drop-in alternative refrigerants in existing systems. The replacement of CFC and HCFC systems by HFC systems is expected to lead to a rapid increase in the use of HFCs globally [IPCC and TEAP, 2005]. Moreover, global economic development has made and is expected to continue to make R+AC systems more affordable for large numbers of people. In industrialized countries the penetration level of refrigerators has already reached more than one per household; similar developments may be expected for developing countries and other applications. The demand for cooling applications such as air conditioners is not only dependent on economic development but may also on the local climate; nonetheless even in a country like the Netherlands with relatively moderate 'normal' summer day maximum temperatures of 22ºC [KNMI, 2008], air conditioners are becoming (increasingly) standard in cars, office buildings, commercial buildings and even in private homes. Economic development in developing countries, which are generally located in climate zones with much higher temperatures, is expected to lead to a further massive increase in refrigeration and air conditioner use. Global warming may add to this increase, both in developing and industrialized countries.

The combined effect of ODS-replacement and economic growth is projected to lead to a growing importance of HFC emissions in the global overall GHG emission. HFC emissions related to R+AC systems are estimated at around 0.4 Gt CO_2-eq in 2002, rapidly increasing to around 1.1 Gt CO_2-eq in 2015 [IPCC and TEAP, 2005]. Further increase may be expected after this date, because of ongoing economic growth and because the constraints on using HCFCs under the Montreal Protocol will become ever more stringent in developing countries.

UNEP [2005] presents disaggregated data on the banks[3] and emissions of F-gases in 2002 and in the 'business as usual' (BAU) scenario projection for 2015 reported in IPCC and TEAP [2005]. It disaggregates into the different types of F-gas (CFCs, HCFCs and HFCs) and into different sectors (refrigeration[4] (REF), stationary air conditioning (SAC) and mobile air conditioning (MAC)) in industrialized[5] and developing countries.

The data, graphically presented in figures 1-4, clearly show the expected transitions in industrialized and developing countries; from CFC and HCFC based R+AC systems to HFC based systems in industrialized countries and from CFC and HCFC based systems to HCFC (and HFC) based systems in developing countries. The data also show that the amount of fluorinated gases, both in banks and emitted, measured in tonnage of substance, rises in all sectors, especially in developing countries where it roughly doubles (see table 2) during the modeled period. Nonetheless, the total GWP of banks and emissions is relatively stable in the projection period, and even decreases in some sectors; the transition from very high GWP CFCs to high GWP HCFCs and HFCs compensates the increasing use of fluorinated gases in the modeled time period. However, because most of the CFC use will have stopped in 2015, GWP weighted bank and emission projections

[3] The term 'banks' of fluorinated gases is used for fluorinated gases contained in applications
[4] In IPCC/TEAP and UNEP, the term 'refrigeration' includes domestic, commercial, industrial and transport refrigeration.
[5] UNEP uses the term 'developed' countries

may be expected to show values increasing at the same pace as the tonnage after this projection period, unless action is undertaken to decrease the use and emission of fluorinated gases in R+AC systems. As noted above, the expected future increase in emissions, most rapid in developing countries, forms the concern underlying the thesis.

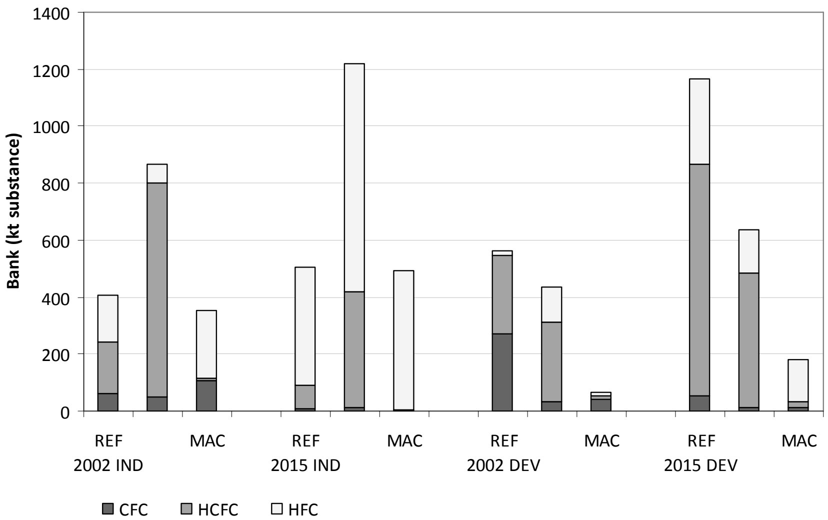

Figure 1.1 F-gas refrigerant bank in different sectors in industrialized (IND) and developing (DEV) countries in 2002 and 2015, in tonnage substance (from: [UNEP, 2005]).

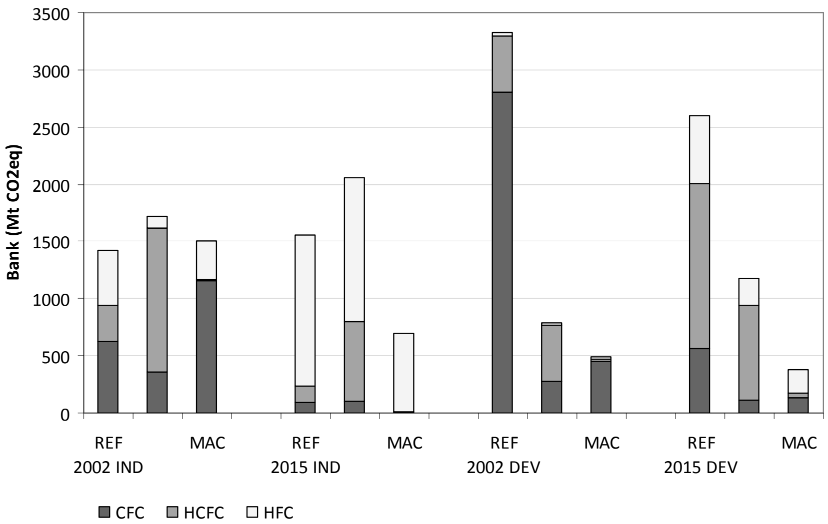

Figure 1.2 F-gas refrigerant bank in different sectors in industrialized (IND) and developing (DEV) countries in 2002 and 2015, in GWP (from: [UNEP, 2005]).

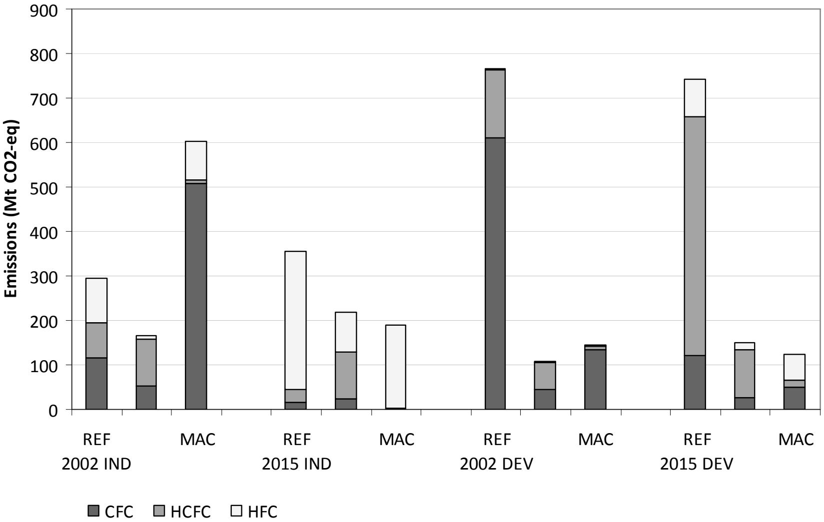

Figure 1.3 F-gas refrigerant emissions in different sectors in industrialized (IND) and developing (DEV) countries in 2002 and 2015, in GWP (from: [UNEP, 2005]).

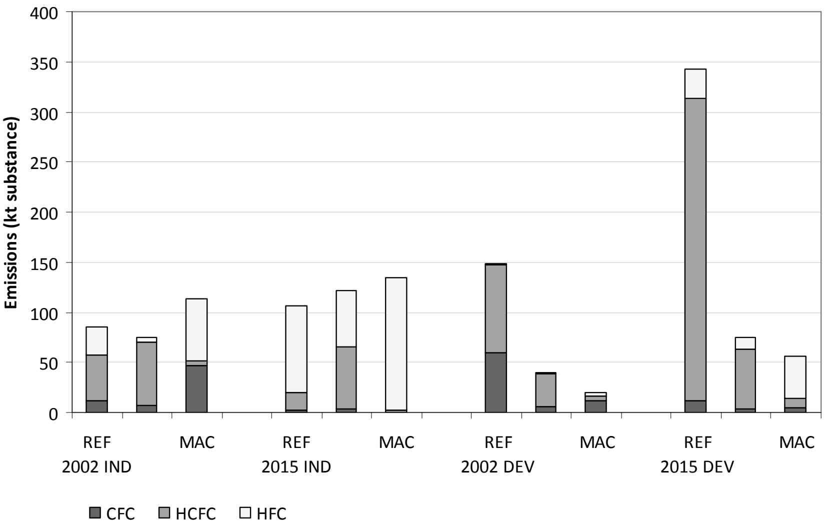

Figure 1.4 F-gas refrigerant emissions in different sectors in industrialized (IND) and developing (DEV) countries in 2002 and 2015, in tonnage substance (from: [UNEP, 2005]).

Table 1.2 Aggregated stocks and emissions of F-gas refrigerants in industrialized (IND) and developing (DEV) countries in 2002 and 2015, in GWP and in tonnage substance (from: [UNEP, 2005])

		(Mt CO2-eq)		(kt substance)	
		2002	2015	2002	2015
Stock	IND	4644	4314	1627	2219
	DEV	4602	4150	1065	1983
Emissions	IND	1062	763	273	363
	DEV	1020	1019	208	473

1.2.4. Energy use

R+AC systems lead to additional contribution to greenhouse gas emissions through their energy use. Many R+AC systems operate on electricity, which is currently mainly generated through the combustion of fossil fuels. Fossil fuel combustion leads to the emission of CO_2. CO_2 emissions from fossil fuel use have the largest share (56.6%) [IPCC, 2007] in the basket of six GHGs defined by UNFCCC. Transforming the global energy system is therefore essential in reducing global GHG emissions to the extent required to prevent catastrophic climate change. The contribution of R+AC systems to global energy use is largely unknown. UNEP [2007a] estimates R+AC systems consume 10-30% of total electricity consumption in industrialized countries. The total global emissions related to electricity generation are estimated at 10Gt CO_2 in 2004 [PBL et al., 2007]. Although electricity consumption related to R+AC systems may (still) be lower in developing countries, a first order approximation combining these numbers suggests 1-3Gt of CO_2 emissions may thus be related to the electricity consumption of R+AC systems globally. This estimation suggests that the contributions to climate change from refrigerant emission and emissions related to energy use are of the same order of magnitude. This is in accordance with findings about the mobile air conditioning and commercial refrigeration sectors in IPCC and TEAP [2005]. In contrast, statements from the sector itself often imply energy use contributes about four times more over the system's lifecycle[6] [EPEE, 2001; IIR, 2005].

The important contribution of R+AC systems to global energy use and its related GHG emissions has resulted in increased attention for energy efficiency in R+AC systems. In principle, the energy consumption of R+AC systems depends on a system's coefficient of performance (COP) and its cooling load. A system's COP is a measure of the energy required to transport a unit of heat out of the system's controlled space. A system's COP depends on various technical design properties, including the type of system, the physical properties of the refrigerant used in the system, the compressor efficiency, joints and valves between various system parts, the desired control temperature and the temperature gradient it needs to maintain. The cooling load depends on, amongst others, the insulating properties of the controlled space and heat loading of the system (e.g. placing warm objects within the controlled space).

[6] A possible explanation for this difference is that an investigation of individual systems may differ substantially from a global assessment.

Energy efficiency plays a role in refrigerant choice although it is not addressed specifically in the thesis. Refrigerant choice may influence system COP and thus may influence system energy use and, in the current energy system, related GHG emissions. Optimizing a system's contribution to climate change aggregated over its functional lifetime may therefore imply balancing the impact of life cycle refrigerant emissions with life cycle energy use. In the light of reducing the sector's contribution to climate change, improving energy efficiency is high on the agenda in the R+AC sector. However, the thesis does not focus on technical system properties and does not address improving energy efficiency of R+AC systems. The thesis largely disregards the effects of efficiency improvements from the perspective of climate change. As noted above, transforming the global energy system is essential in any successful climate change strategy. The thesis does not investigate such energy transition; reflections on such transition can be found in many other studies (e.g. [Schenk, 2006; Ummels, 2009]). Instead, the thesis presumes that a transition to a fully carbon neutral energy system will gradually be realized. This presumption is based on the argument that if the energy transition will not be successful, other initiatives to reduce GHG emissions would have only a marginal effect on actually limiting climate change. Thus, the thesis reflects on reducing the climate impact of R+AC systems from the perspective that doing so actually makes sense.

The consequence of such presumption is that the contribution to climate change of energy use may be expected to decrease over time. This means that the relevance of including the effects of energy use on the total climate effect of R+AC systems depends on the assessment's temporal scale. In a short term assessment, energy effects should be included, but in a long term assessment, such effects may be neglected from a climate perspective.

Regardless of energy use's contribution to climate change however, R+AC system energy use is important from the perspective of power capacity planning. For a well functioning society, energy supply needs to meet energy demand at all times. Especially in the case of electricity, an inappropriate balance between supply and demand may lead to grid failure and black outs, with potentially severe societal consequences. R+AC system energy use is not constant, but may be expected to fluctuate over time. Apart from 'normal' cooling demand variation related to variation in economic activity, R+AC energy use is temperature dependent: it varies with oscillating temperatures in the diurnal and seasonal cycle and may therefore contribute to intermittency events on the electricity grid. An increasing use of R+AC systems may therefore require adaptation of power generating capacity planning. The increasing average global temperature due to the emission of GHGs, may further influence the future energy demand by R+AC systems. The relation between energy demand and temperature is discussed in chapters 6 and 7.

1.3. Socio-economic mechanisms underlying environmental pressure

The physical nature of environmental pressures necessitates a comprehensive physical understanding of their causes and effects. Many environmental studies therefore aim at improving such physical understanding. Such studies typically aim at either clarifying or quantifying observed environmental pressures and related dangers or projecting environmental pressures in the future. Moreover, environmental studies often aim at finding more environmentally benign approaches for certain activities that can replace current approaches. Apart from studying environmental problems for the sake of understanding, such studies generally have the overarching aim to contribute to resolving current or preventing future environmental degradation. Physically oriented studies typically point to the need to alter the anticipated course of societal development and propose changes to current activities that may lead to such altered course. Studies addressing greenhouse gas emissions from R+AC systems generally form no exceptions to this pattern (e.g. [IPCC, 2007; IPCC and TEAP, 2005; UNEP, 2007a; WMO, 2007]). Mostly such studies quantify current or future GHG emissions from R+AC systems and technological options to reduce these.

However, research from social sciences shows that it is also essential to understand *why* certain activities are currently undertaken in the way they are (e.g. [Schreuder, 2009a; Steg, 2003]) and *how* the required changes can be realized (e.g. [Bressers, 2004; Klok, 1991; Mitchell, 2006]). The current socio-economic system does not specifically aim at causing environmental damage. Therefore, there must be underlying causes for the current state of the system that may need to be addressed in order to achieve a lasting system change. Such causes may be found in the *socio-economic structures* (institutional, regulatory, economic, historical and behavioral) that underlay socio-economic systems. Studying these socio-economic structures may address the questions *how* and *which* changes should be effectuated in the socio-economic system and *who* should effectuate such change.

A typical underlying cause of environmental damage is that the stakeholder(s) responsible for environmental pressure often do not bear the full costs of the related damage. Rather, such costs are often borne by different stakeholders or, in the case of global environmental problems, shared collectively. Due to such 'externalization' of environmental costs related to socio-economic activities, individual stakeholders pursue activities that are suboptimal from a collective perspective [Coase, 1960; Hardin, 1968].

Moreover, multiple stakeholders are often involved throughout the life cycle of a certain product or service, which may obscure responsibility. For instance in the case of R+AC systems, system manufacturers, system operators, system maintenance engineers and disposal facility operators have economic stakes throughout the life cycle of R+AC systems. The different activities by these stakeholders are interdependent; the design of the system by the manufacturer directly influences the system's emission profile throughout the rest of its functional lifetime; the maintenance regime maintained by the system operator determines the required frequency of servicing and also influences the remaining charge of refrigerant at the end of life, which determines the possible emission during disposal. In the R+AC system's lifecycle, the opportunities to influence system performance thus generally decreases from 'upstream' to 'downstream' stakeholders. The power relations in the sector (the ability to dictate the course of sectoral developments, including lobbying power to influence related policy) may be expected to run parallel. Systems' manufacturers can dictate their system designs to downstream stakeholders, because of their powerful position at the start of the systems' life cycle and their economic and informational advantage. However, as noted, refrigerant emissions occur mainly in the downstream life cycle phases of use and disposal. The extent of each stakeholder's responsibility for environmental pressure throughout the life cycle is therefore a matter of debate. The thesis discusses the consequences that such interdependencies have for effective emission mitigation strategies. It emphasizes the role of stakeholders and their individual capacities in effective climate policy.

Introducing certain physical options to change the environmental pressure from activities generally requires adaptations in the socio-economic structures (and the other way around!). E.g. price incentives, information or institutional capacity to enhance regulative enforcement may be required to change stakeholder behavior. Failing to change the socio-economic structures may thus lead to failing to implement the desired physical option. Conversely, this means that if socio-economic structures cannot be changed, certain physical options should not be aimed for. Thus, the socio-economic structures may set conditions for physical approaches to alleviate environmental pressures and vice versa. Multidisciplinary research shows that apart from improving physical understanding, integration of physical sciences with social sciences is needed in order to successfully resolve current or prevent future environmental degradation [Schoot Uiterkamp and Vlek, 2007]. Physical scientists may underestimate socio-economic barriers, and social scientists may not fully appreciate the physical limits of technological solutions. If physical and socio-economic systems are analyzed separately, as is often the case, the interdependencies between these systems may therefore be neglected, possibly resulting in choices to resolve (future) environmental degradation that are ineffective due to unforeseen barriers.

From this perspective, the thesis aims at integrating understanding of the physical mechanisms and understanding of the socio-economic structures underlying the current and anticipated environmental pressure related to R+AC systems and the ways that altering these structures may reduce such environmental pressure.

1.4. Local variation and their consequences in global policies

The global impact of climate change, the need for global effort in mitigation, and the globalization of the economic system almost automatically result in a global perspective on climate policy, highly similar to the ozone policy process. Still, even though emissions cause global impacts, they stem from local activities under local circumstances.

As noted in earlier sections, R+AC systems serve a multitude of societal functions and involve many and very diverse stakeholders throughout the world. Different stakeholders may have different preferences and may act accordingly. Stakeholders in a globally competing market may act differently than stakeholders that operate on a local market. Stakeholders in developing countries may act differently than stakeholders in industrialized countries. Each stakeholder generally operates within his own realm of economic stakes, available resources, socio-economic developmental state, government regulation, culture, habits, prevailing climate, and etcetera. Each of these stakeholder characteristics may interact with the (local) effectiveness of policy strategies [Bressers, 2004].

International climate agreements acknowledge the different circumstances between developing countries and industrialized countries. In the UNFCCC and the resulting Kyoto Protocol developing countries and industrialized countries have accepted “common but differentiated responsibilities” [UN, 1992b; UN, 1997]. Industrialized countries have contributed much more to total cumulative emissions than developing countries, especially on a per capita basis and may thus be seen much more responsible for global warming. Moreover, developing countries have limited current capacity to address such a long term issue as climate change while they are still struggling with more pressing issues on a daily basis. Economic development leading to poverty relief and hunger relief may logically be seen as more crucial policy targets in these countries. However rapid economic development in developing countries following the same development pathway as industrialized countries leads to a rapid increase in these countries' contribution to global GHG emissions. Physical assessments show that the limited remaining emission space to stay within 2ºC warming implies that developing countries cannot follow the same development path as industrialized countries [Baer et al., 2008]. Thus, a globally effective strategy should enable developing countries to deviate from the development pathway followed historically by industrialized countries, but should still lead to socio-economic progress in these countries.

Neglecting the importance of such local preconditions for mitigation approaches may reduce global policy effectiveness. Therefore, the thesis includes the role of variation in local circumstances for the effectiveness for certain policy strategies.

1.5. Research aims and questions

This thesis' main goal is to improve the understanding of interactions between physical, socio-economic and policy systems in mitigating high-GWP refrigerant emissions from refrigeration and air conditioning systems. Moreover, it aims to contribute to a better understanding of the relation between energy demand and outdoor temperature.

The main research question of the thesis is:

> *"What are the consequences of the interaction between physical, socio-economic and policy systems for mitigating high-GWP refrigerant emissions in an effective long term climate strategy?"*

A related research question is:

> *"Can increasing refrigeration and air conditioning use be observed in past energy demand and how can such changes be included in global energy demand models?"*

The main question is addressed in chapters 2 to 5 of the thesis. Each chapter investigates different aspects of the interaction between the physical, socio-economic and political systems and answers one of the sub questions described below. The second question is discussed in chapter 6 and 7. The following section describes the sub questions addressed in each chapter and serves as a reading guide.

1.6. Subquestions and reading guide

Chapter 2 principally addresses the question:

> *'Does climate policy design influence stakeholder cooperation?'*

The chapter discusses the importance of social processes in global policy strategies. It elaborates on the policy design in the Montreal Protocol and the Kyoto Protocol, which are central to the research theme of the thesis. The Montreal Protocol is generally perceived as very successful whereas the Kyoto Protocol is often perceived less so. Based on social dilemma theory, the chapter suggests that differences in policy design that affect uncertainty for stakeholders, number of stakeholders involved, and number of available abatement options may influence stakeholder cooperation. It compares each of the two international agreements' designs regarding these characteristics and links the outcome of this comparison to their relative effectiveness.

Chapter 3 principally addresses the question:

> *'What consequences does the Montreal protocol have for the global warming potential of fluorinated refrigerant emissions in rapidly developing China?'*

The chapter quantitatively projects future refrigerant emissions in China, which serves as a model for rapidly developing countries. It investigates the influence of the recent Montreal Protocol amendment on projected Chinese fluorinated greenhouse gas emissions. Furthermore it discusses the consequences of the exclusion of ODS under the UNFCCC. It thus reflects on the consequences of global policy agreements on local emission pathways and on the interpretation of physical assessments.

Chapter 4 principally addresses the question:

> *'What consequences do various mitigation strategies have for the emissions of HFC refrigerants in Germany?'*

The chapter further investigates the interface between the physical system and the policy system. It models and projects future refrigerant emission pathways from different mitigation policy strategies, taking into account socio-economic conditions for policy implementation. In contrast to the model in Chapter 3, the model in this chapter is based on assumptions that aim to represent the situation in an industrialized country.

Chapter 5 principally addresses the question:

> *'Which policy strategies can be effective in mitigating high global warming potential refrigerants globally, taking into account the various conditions set by the physical, socio-economic and policy systems?'*

The chapter investigates how the local variation in socio-economic and institutional systems influences the global opportunities to control emissions from the physical system. It discusses how approaches to mitigate global refrigerant emissions from refrigeration and air conditioning systems need to acknowledge the differences between developing and industrialized countries in order to form an effective contribution to a long term climate policy.

Chapter 6 principally addresses the question:

> *'Which changes can be observed in the temperature dependence of electricity demand in the Netherlands?'*

The chapter hypothesizes that an increasing use of refrigeration and air conditioning systems in a country may influence the temperature dependence of its total national electricity demand. It analyzes the historic development of the electricity demand pattern in the Netherlands based on daily electricity consumption and daily temperature data.

Chapter 7 principally addresses the question:

> *'How may the temperature dependence of energy demand be expected to change in the future and how do current energy models accommodate for such changes?'*

The chapter further discusses the temperature dependence of energy demand from a global perspective. It discusses the current practice to assess future energy demand through temperature dependence patterns in models. It models the effects of assumptions in current energy demand models in the context of climate change.

Chapter 8 integrates the findings of chapters 2-7 and discusses the results. Finally it returns to and answers the main research questions in a final conclusion to the thesis.

2. Policy design distinctions in the Montreal Protocol and the Kyoto Protocol; considering cooperation of stakeholders[1]

Abstract *The main explanation for the low effectiveness of the Kyoto Protocol compared to that of the Montreal Protocol, is that the number of stakeholders and level of uncertainty involved in climate policy is much larger than in ozone policy. The literature on social dilemmas shows that larger group size and higher level of uncertainty may lead to lower cooperation by stakeholders. This chapter aims to explore and assess how policy design distinctions in the Montreal Protocol and the Kyoto Protocol affect these characteristics. The chapter differentiates between "intrinsic" policy design distinctions based on the physico-chemical differences between both environmental issues and the ties of greenhouse gases and ozone depleting substances with society and "non-intrinsic" design distinctions based on other, such as economic, arguments. The results show that many of these policy design distinctions further increase group size and uncertainty for stakeholders and thus may help to explain the lower effectiveness of the Kyoto Protocol compared to the Montreal Protocol. The chapter argues that a future climate policy should incorporate measures to reduce group size and uncertainty.*

2.1. Introduction

The environmental threats of stratospheric ozone depletion and climate change have much in common. Both result from emissions of substances from societal processes into the atmosphere. Both result in threats to human and environmental security on a global and temporarily distant scale. In both cases the largest share of emissions originates from industrialized countries, though ultimate resolution requires cooperation of both

[1] This chapter is an expanded version of Hekkenberg and Schoot Uiterkamp (2009). *Improving stakeholder cooperation in post Kyoto climate policy.* Climate Change: Global risks, challenges and decisions. IOP Conference series Earth and Environmental science 6.222012. doi: 10.1088/1755-1307/6/22/222012. IOP Publishing.

industrialized countries and developing countries to prevent global disaster. In both cases stakeholders from all over the world are required to cooperate to achieve success.

The policies to resolve both issues, the Montreal Protocol [UN, 1987] and the Kyoto Protocol [UN, 1997], respectively, are also closely related [Oberthür, 2001]. And yet, the Montreal Protocol seems to work effectively, whereas the Kyoto Protocol seems not capable of reducing greenhouse gas (GHG) emissions globally. Reports to UNEP [UNEP, 2008] show that almost all countries neatly comply with their phase-out schedule under the Montreal Protocol. Reports to UNFCCC [UNFCCC, 2008b] indicate that many parties may not manage to achieve their designated Kyoto targets. An investigation of the differences between both treaties and their consequences, may point to opportunities to increase the effectiveness of the climate regime, which may be valuable in the current debate on a post-Kyoto climate regime. The recent celebrations of the 20th anniversary of the 1987 Montreal Protocol and the 10th anniversary of the 1997 Kyoto Protocol seem the perfect occasion for such a comparative assessment of these international environmental treaties.

The different effectiveness of both treaties may be explained partly by the *intrinsic* differences between both environmental threats. Important differences exist in the physico-chemical mechanisms resulting in climate change or ozone depletion, and in the function of and dependence on GHGs and ozone depleting substances (ODSs) in society. These differences result in a much larger number of stakeholders and processes involved in climate policy, and a much greater uncertainty on the economic effectiveness and necessity of different climate policy options. Policy makers have made distinctions in the design of the Kyoto Protocol and the Montreal Protocol to deal with these intrinsic differences. However, policy makers have also made distinctions in the design of both treaties for other (*non-intrinsic*) reasons. Both intrinsic and non-intrinsic design distinctions may help to explain the difference in effectiveness between the Kyoto Protocol and the Montreal Protocol.

This chapter aims to critically explore these policy design distinctions in order to contribute to the debate on the post-Kyoto climate policy. The chapter compares both treaties, following the various stages of policy design. First it compares the *object* of the policy (what is considered to be the problem?), then the chosen *goals* (what does the policy want to achieve?), and lastly the distinctions in policy *instruments and specifics of implementation* (how will the policy achieve this?), including policy boundaries. It differentiates between intrinsic design distinctions and non-intrinsic design distinctions in order to assess possible improvement options. Obviously, if one wants to compare both policy designs abstraction of some of their specifics to a level that makes comparison possible is necessary.

2.1.1. Kyoto Protocol

IPCC [2007] shows rapidly increasing global GHG emissions, from 39.4 Gt CO_2-eq in 1990 to 49 Gt CO_2-eq in 2004. The Kyoto Protocol has obviously not yet resulted in a decline in global greenhouse gas (GHG) emissions. National reports to UNFCCC show that GHG emissions in Annex I[2] countries have decreased 2.6%[3] between 1990 and 2005 [UNFCCC,

[2] Annex I of the Kyoto Protocol lists the countries that have committed themselves to GHG-emissions limits.

2008b]. However, a closer look at these emission figures shows that without counting Russia[4], Annex I emissions have increased. Although this result may seem disappointing, numerous projects and measures have been implemented that have reduced emission rates, or at least prevented a stronger growth on national or smaller scales. Given the economic growth in most Annex I countries since 1990 [WRI, 2008], a relative decoupling between economic growth and GHG emissions has been established.

The conference of the parties to the UNFCCC has recently *"recogniz[ed]* that deep cuts in global emissions will be required to achieve the ultimate goal of the Convention .." [COP-13, 2007]. Metz et al. [2002] suggest that in order to stabilize the atmospheric concentration of GHG, global emission rates need to be brought down ultimately to less than 50% of current values. In order to keep the option of stabilizing atmospheric concentration of GHGs at a relatively low level, global emission rates will need to be brought below current rates before the middle of this century.

To achieve these kinds of global emission reductions, the current climate regime will not suffice. Much deeper cuts in emissions are required in industrialized countries. Moreover, involving developing countries in the global effort is a prerequisite to future success, because their recent and projected rapid economic development, combined with projected population growth will lead to a rapid increase in GHG emissions in these countries. The Kyoto Protocol is therefore only considered a "first step towards a truly global emission reduction regime that will stabilize GHG concentrations at a level which will avoid dangerous climate change" [UNFCCC, 2008d]; future amendments should be added to achieve the ultimate goal of the UNFCCC.

2.1.2. Montreal Protocol

In contrast to the relatively small successes achieved by the international climate policy thus far, the international policy on preventing stratospheric ozone depletion seems to remain very effective. The provisions made in the Montreal Protocol, if they continue to be complied to, ensure that production and consumption of ozone depleting substances (ODSs) is phased out globally and that emissions of these substances will cease eventually. Already atmospheric concentrations of CFCs, which are considered to be amongst the most potent ODSs, show to level off or to be slowly declining [WMO, 2007]. Because of the long atmospheric lifetimes of many of the substances involved, the concentration of active chlorine in the atmosphere will drop only slowly. Therefore recovery of the ozone layer to pre-ozone-hole levels is expected to take until around the middle of this century [WMO, 2007]. Even though measurements of the Antarctic ozone hole show that 2006 had one of the largest and deepest holes in history [NASA, 2008], ozone depletion is generally considered an historic issue as far as policy is concerned. The 2007 amendment [UN, 2007] which tightened some of the last loose ends to the Montreal Protocol shows[5] how the international community effectively "controls" the threat of ozone depletion.

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[3] Emissions excluding Land Use Change (LUC); including LUC, the emission reduction is 4.2%,

[4] Emissions in Russia decreased sharply after the economic collapse that followed the 1991 revolution.

[5] A rough calculation shows this amendment to the Montreal Protocol may reduce HCFC production and consumption in developing countries by 22Mt and 23Mt respectively.

2.2. Intrinsic differences

As mentioned above, some of the distinctions in policy design result from the differences in the physico-chemical mechanisms leading to climate change and to ozone depletion, and the functional position of GHGs and ODSs in society. In this section these matter-based and functional position-based differences, which are defined as the "intrinsic" differences are elaborated on.

Firstly, the physico-chemical mechanisms underlying ozone depletion and climate change are quite different, leading to a different problem perception at a meta level. Any decrease in ozone levels may lead to increase of malignant diseases, ecosystem damage and decrease of crop yields [Fahey, 2007]. Any decrease of stratospheric ozone is therefore unwanted. Since each molecule of ODS is able to decrease ozone levels, the optimal rate of ODS emission is no emission at all. In the case of climate change, the picture is quite different. Here too each molecule of GHG is able to enhance the greenhouse effect (relative to its global warming potential). However, it is not only a changing climate itself that is thought to be the core of the problem; the problem is also thought to be the rate of change, combined with human and natural resilience to adapt to this change [IPCC, 2007]. The natural system is expected to be able to adapt to higher GHG concentration, e.g. through feedback loops in the carbon cycle. Some anthropogenic GHG emission is therefore thought to be acceptable. Only GHG emissions over a certain threshold are thought to be damaging.

Secondly, the abundance of processes leading to GHG emissions is much larger than those leading to ODS emissions. GHG emissions result from many processes at all societal levels, ranging from industrial to individual processes. Many processes require energy; in contemporal society a large share of this energy is provided by the combustion of fossil fuels, which leads to GHG emissions. Emissions of GHG can be localized at large point sources (e.g. power plants), distributed over a multitude of small (mobile) point sources (e.g. cars), or result diffusely from land use change (e.g. drained peat land). The use of ODSs is limited to a couple of products from a handful of industrial sectors. The number of processes leading to GHG emissions is therefore much higher than in the case of ODS. Climate policy thus "intrinsically" affects a much higher number of processes, and therefore a much higher number of stakeholders than ozone policy.

Thirdly, especially because of their link to energy use, GHG emissions are tightly woven into the fabric of society. For many economic activities energy consumption is a prerequisite, which cannot easily be avoided. The use of ODSs is much less intertwined with society. Generally, intervention in GHG emissions has a much larger impact on society and economy than intervention in ODS.

Fourthly and fifthly, ODSs are used only in relatively few sorts of applications, and are used for their physical and chemical properties, ie. their functionality. Alternatives that could equally function in these applications were relatively easily discovered. Most GHGs are not used intentionally for their functional properties, but result as a waste from numerous processes. These processes are widely distributed throughout societal sectors. Therefore, in the case of GHG emission reduction, alternatives need not to be found for the GHGs themselves, but for the processes that lead to these emissions. This often requires the redesign of processes, which usually involves more than just replacing a substance, especially for processes that require energy. Even in sectors that do use GHGs for their functional properties, e.g. the refrigeration sector that uses fluorinated gases as refrigerants, substituting these GHGs is often regarded as difficult, because of possible interference with energy efficiency [Little, 2002].

Sixthly, ODS are basically purely man-made; there are hardly any known natural sources or sinks of ODS, apart from the atmospheric processes in which the ozone depleting active chlorine radicals are formed [Molina and Rowland, 1974]. In contrast, there is an abundance of natural processes that influence atmospheric GHG levels, e.g. plant photosynthesis, oceanic uptake of CO_2 or food digestion in animals. GHG levels in the atmosphere are thus only partially under anthropogenic influence, whereas anthropogenic influence of ODS is virtually absolute.

Seventhly, because of the existence of natural processes there are additional options to reduce GHG concentration in the atmosphere, that do not exist in case of ODS. Stimulating the natural CO_2-uptake may potentially compensate GHG emissions, whereas it is virtually impossible to recapture ODS on a large scale once a molecule has been emitted into the atmosphere.

Lastly, the issues of ozone depletion and climate change differ markedly with regard to their perceived urgency. Ozone depletion with its imminent danger to human health and the familiarity of the general public with the dreadful results (notably cancer), has little problem of building capacity for political intervention. Capacity building for political intervention to prevent climate change is much more difficult. The threat of climate change is apparently much more difficult to understand for a general public [Bord et al., 1998; Dunlap, 1998], possibly because the problem description is more vague and uncertain, and distant in time. Moreover, Leiserowitz [2005] found that, in the USA, most people do not have “vivid, concrete and personally relevant affective images of climate change”, and neither do they link climate change to human health problems. Arguably, publicly perceived urgency may change rapidly by certain dramatic events. In case of ozone depletion, the discovery of the ozone hole over the Antarctic [Farman et al., 1985] undoubtedly increased perceived urgency. Some important recent publications on the effects of climate change [Gore, 2006; IPCC, 2007; Stern, 2007] and the occurrence of extreme weather events with high numbers of casualties or large economic damage may

Table 2.1 Functional and matter-based differences between ODS and GHG and between the issues of Ozone Depletion and Climate Change

	ODS / Ozone Depletion	GHG / Climate Change
1	Optimum emission rate “zero”	Optimum emission rate “below threshold”
2	Limited number of processes and sectors	High number of processes and Sectors
3	Weak link with economy	Strong link with economy
4	Mainly functional product	Mainly waste products
5	Alternatives readily available	Alternatives difficult
6	No natural sources or sinks	Natural sources and sinks exist
7	No ‘outside system’ reduction options	Additional reduction options
8	High perceived urgency – high capacity for policy	Vague and distant problem – low capacity for policy

increase perceived urgency in the case of climate change. Table 2.1 provides an overview of these intrinsic differences.

2.3. Stakeholder cooperation: Group size and uncertainty in social dilemmas

Managing a globally acceptable rate of GHG emissions requires cooperation between all the stakeholders. Emissions from each individual, process, or country should add up to no more than the globally agreed target. Achieving this globally agreed target may generally be considered of common interest[6]. However, a conflict may exist between individual interests and the common interest, leading to a so called 'social dilemma'. Especially when individual influence on the collective result is limited, individual interests are often served best by noncooperation: In case others do cooperate the issue is resolved without cost to the non-complier, in case others do not cooperate either at least the non-complier did not pay in vain. Managing the global emission target can thus be regarded a classic social dilemma. As exemplified by Hardin's "*tragedy of the commons*" [Hardin, 1968], such social dilemmas run a high risk of collective noncooperation, resulting in a collectively suboptimal situation. The current international policies on climate change and on ozone depleting substances, may be regarded two tiered commons dilemmas: National governments collectively face a global target, whereas national stakeholders collectively face a national target. Our arguments about stakeholders and uncertainty are aimed mainly at the level of individual stakeholders, although some may also be valid on the governmental level.

Dietz et al. [2003] describe how the ways of organizing activities, which they call 'human institutions', are very important in managing social dilemmas. This chapter focuses on the consequences of policy design on cooperation in social dilemmas, by investigating its effect on the number of stakeholders that are collectively responsible to achieve the target and the level of uncertainty on the economic efficiency of available reduction options. As will be described below, these parameters may influence cooperation of stakeholders in a social dilemma, and consequently, policy effectiveness.

The standard literature on commons dilemmas assumes that larger groups tend to evoke lower cooperation by individual stakeholders due to a lower perceived individual efficacy, lack of trust, lack of group identity, and a higher chance to go unnoticed [Biel and Gärling, 1995; Carpenter, 2007; De Cremer and Leonardelli, 2003; Kerr, 1989; Steg, 2003]. Increasing group size, e.g. by setting aggregated targets, may thus result in lower cooperation. Carpenter [2007] further argues that especially the diminishing possibilities to monitor lead to reduced cooperation in larger groups. This emphasizes the importance of monitoring in a climate regime. Steg [2003] provides a valuable review of structural, group, and individual characteristics that influence cooperation in commons dilemmas.

The existence of uncertainty on various levels may influence stakeholder cooperation through several mechanisms [Biel and Gärling, 1995]. Firstly, research on resource dilemmas shows that a higher uncertainty in resource pool size, may result in overextraction by the stakeholders [Jager et al., 2002; Steg, 2003]. If one assumes that the global emission target may be regarded as a resource pool, uncertainties in the future emission targets may thus lead to lower cooperation by stakeholders. Secondly,

[6] Countries that are expected not to be influenced, or influenced positively by climate change may not share this common interest.

uncertainty may exist about the economic efficiency of various reduction options. Such uncertainty may be regarded a regular part of investment decisions. Standard investment theory dictates to incorporate this risk in the cost-benefit analysis and base investment decision on the options' discounted net present value. Uncertainties on the duration of a policy, the expected technology improvement, and future targets may thus influence the ranking of different investment options, including the no-investment option. Moreover, uncertainty may exist about the cooperation of others. If competitors do not cooperate, cooperation may mean competitive disadvantage.

The chapter also considers the number of reduction options that are available. The number of reduction options may have two opposite effects on stakeholder cooperation. Generally, psychological theory and research has demonstrated that having the option to choose may increase stakeholder motivation and perceived control compared to having no choice [Iyengar and Lepper, 2000][7]. Having more options on an individual stakeholder scale may therefore be regarded positively for stakeholder cooperation. However, additional reduction options on a national or global scale, may not all be available or feasible for individual stakeholders. Increasing the number of available options often increases the number of stakeholders involved. In this regard, the effect of more reductions options runs parallel to the effect of more stakeholders. Moreover, a higher number of reduction options may also increase the complexity of the decision problem, and thus the uncertainty for stakeholders to make the "right" choice. In this regard the effect of more reduction options thus runs parallel to the effect of higher uncertainty. The effect of the number of reduction options should thus be differentiated between reduction options actually available to individual stakeholders and number of reduction options available in total.

The following sections will present a comparative assessment of the design distinctions between the Kyoto Protocol and the Montreal Protocol and their influence on the number of stakeholders, number of reduction options, and the level of uncertainty.

2.4. Policy subject: Sources and effects of a basket of substances

The Kyoto Protocol and the Montreal Protocol are internationally ratified policy schemes resulting from international conventions. The Kyoto Protocol results from the United Nations Framework Convention on Climate Change (UNFCCC) of 1992, the Montreal Protocol results from the Vienna Convention for the Protection of the Ozone Layer of 1985. The stated goal of the UNFCCC is to

> *"achieve stabilization of greenhouse gas concentrations in the atmosphere at a low enough level to prevent dangerous anthropogenic interference with the climate system"* [UN, 1992b].

[7] Iyengar and Lepper [2000] also show that for individual decision making, having too many options may lead to "detrimental consequences for human motivation", even if having more options appeared to be more desirable. However, the number of alternative reduction options for individual stakeholders is unlikely to be beyond this point, thus this effect is not included in our discussion.

The goal of the Vienna Convention is

> *"to protect human health and the environment against adverse effects resulting or likely to result from human activities which modify or are likely to modify the ozone layer"* [UN, 1985].

Both conventions thus aim at preventing negative effects. The Montreal Protocol aims to achieve this through eliminating the underlying societal *sources* of these effects, by phasing out production and consumption of ODS. It thus ensures that at some point in the future, no more ODS will enter the atmosphere. The Kyoto Protocol more broadly targets the sources' *effects*, aiming at managing the GHG emissions to the atmosphere at an acceptable rate. This approach can still lead to elimination of undesirable sources, but emphatically leaves open other mechanisms, such as reducing emission intensities, end-of-pipe emission treatment, emission capture and storage and (re-) forestation, as these measures can reduce climatic effects without the need to drastically intervene in the economic system. The Kyoto Protocol states no preference for any one of these options.

Global warming, as well as ozone depletion, originates from a multitude of substances. The potential of each substance to contribute to the problem depends on its physico-chemical properties. The concepts of global warming potential (GWP) and ozone depleting potential (ODP) have been introduced, in order to compare and calculate effects of different substances.

The current climate regime is based on the logic that ultimately, climate change is due to the cumulative effects of the various emissions; physically, it does not matter which GHG gives rise to the radiative forcing. Reduction targets are therefore given only at the aggregated level; countries may decide for themselves which substances they wish to reduce to achieve their targets. Apart from respecting each nation's sovereignty, this approach is also thought to be the most efficient from an economic viewpoint; reductions may be achieved against the lowest marginal abatement costs.

In the Montreal Protocol, instead of aggregating the various substances, the substances are divided into different categories, for each of which separate targets have been set. The categories are based upon chemical characteristics of the substances. Although several substances are used in several industrial sectors, and several industrial sectors use substances from several categories, this division limits the number of parties per target; in many cases, a limited number of sectors dominates the use of certain substances (see eg [McCulloch, 1999]). The division in categories therefore unmistakably addresses these sectors' responsibility towards the problem. In contrast, by aggregating a multitude of substances from a multitude of sectors, the design of the Kyoto Protocol leads to the highest possible number of stakeholders to share responsibility.

2.5. Policy goal: Temporary reduction vs. final elimination

Currently, no ultimate future reduction target has been set in the global climate regime[8]. An agenda for negotiations on future climate policy has only recently been set and is

[8] On a smaller scale, some future targets do exist: The EU aims at 20% reduction of GHG emissions in 2020, and 50% reduction in 2050 [European Commission, 2008]. UNFCCC negotiations aim at stabilizing emissions in the coming 10-15 years, and "dramatically reduce" them by 2050 [UNFCCC, 2008a].

scheduled to result in an agreement at the end of 2009 [UNFCCC, 2008a]. There is little doubt that some anthropogenic emission of GHG will remain to be allowed. This is in sharp contrast with the targets in the Montreal Protocol, which ultimately aims to totally phase out all ozone depleting substances. Any additional loading of the atmosphere with ozone depleting substances is considered to be unwanted, because it would lead to a delay of the restoration of the ozone layer to pre-ozone-hole levels. Additional loading with greenhouse gases is thought to be less problematic, as already explained in section 2.2.

The fact that the globally acceptable rate of GHG emission will be higher than zero creates new difficulties in the process of climate policy formation. Scientific research has not yet answered the question which rate of GHG emissions would ultimately be acceptable[9]. The many steps between GHG emission and ultimate impact create a high level of uncertainty. The specification of the final target rate is therefore subject to political debate. Experience from the Montreal Protocol shows that scientific uncertainty does not need to be an obstacle for an international agreement. The 'Montreal history' shows that its first targets were set without a clear picture of all causes and effects. In the face of new scientific evidence, the protocol was amended several times. In case of the Montreal Protocol, each amendment implied a tightening of its requirements, although in principle the target could also be relaxed when scientific evidence would support it. To complicate things further, even if the effects of each concentration of GHGs could be predicted accurately, climate change impacts will probably vary around the world. Different governments may therefore find different rates of GHG emissions to be acceptable. This means that some type of compromise is required to set a global target for global emissions. So far though, international negotiations have not lead to agreement on a final target. The Kyoto Protocol therefore sets only a temporary target, without indicating what will be next. Since the target is relatively low and excludes a large share of global emissions, it is highly unlikely that it would be sufficient to achieve a stabilization, let alone a reduction of GHG emissions. The treaty should therefore be seen more as symbolic policy, or a first step in a series.

However, the absence of a future target in the climate regime leads to uncertainty for the stakeholders involved. This uncertainty makes investment decisions more difficult, because stakeholders risk competitive disadvantage in case of making the wrong decision. Uncertainty may make risk averse stakeholders hesitant to act, and may make them wait for more clarity. The Kyoto Protocol's lack of future target thus contrasts sharply with the Montreal Protocol, which left stakeholders little doubt that only those stakeholders that would change their activities, would stay in business. Under the Kyoto Protocol, stakeholders may choose to adhere to minimal or temporal adaptation of their activities, and wait whether the future will allow them to restore their normal activity pattern.

[9] Policy documents often refer to a certain level of acceptable temperature change over a certain time frame instead of referring directly to a corresponding atmospheric GHG concentration or GHG emission rate.

2.6. Policy formation: Global uniformity versus national differentiation

Both the Montreal Protocol and the Kyoto Protocol have delegated the global responsibility to national governments. By following this approach rather than agreeing to a common set of detailed technical international laws, participating countries retained their sovereignty over domestic measures. Experiences from both the Montreal and Kyoto treaties, as well as other policy examples, show that countries will sometimes choose different measures to achieve their national policy target. For example, in reaction to the Montreal Protocol, the Netherlands has discouraged HCFC use at an aggregate level by a set of procedural rules (eg [Staat der Nederlanden, 2003]), whereas the USA has implemented differentiated phase-out dates for various HCFC substances [ARAP, 2007]. However, because of its ultimate goal of ODS elimination, the Montreal protocol leaves relatively little room for really deviant legislation. In reaction to the Kyoto Protocol, most countries have formulated a national GHG strategy, with various measures, rules and projects that should lead to achieving their national target.

Nationally differentiated policy may increase national stakeholder involvement in the policy, because of a better fit to circumstances and a smaller stakeholder group size compared to a global policy. There is quite some variety in societal, economic, political and legal structure amongst countries, which may lead to different preferences for certain policy measures. However, setting nationally differentiated policy may create competition disadvantages for internationally oriented companies that may have to deal with different legislation for different countries. Moreover, efforts to create a uniform trade-environment for companies, such as the in the WTO and the EU, sometimes prevent introduction of legislation that possibly imposes trade barriers. Therefore, national governments are hard-pressed to create legislation that is neither disadvantaging to the domestic economy nor to foreign competitors. Thus though in theory freedom to set legislation nationally exists, in practice national initiatives often involve voluntary agreements with industry instead of restraining command and control legislation. In the EU there are some notable exceptions, such as the EU-ETS and the recent regulation on fluorinated gases, in which concerted action across a large group of countries limits the effects on the domestic competitive position.

2.7. Policy Instruments: Command and control versus market mechanisms

Neither the Kyoto Protocol nor the Montreal Protocol prescribes which measures individual countries should take to attain the agreed targets. However, because the Montreal Protocol aims at eliminating the sources of the emissions rather than (reducing) the emissions themselves, the only realistic policy measure that will ultimately result from the Montreal Protocol is a ban on the use of certain substances. In the Kyoto Protocol, a whole range of options remains available to national governments, none of which is explicitly advocated in the Protocol. How to comply with their targets is left to the national governments. However, the introduction of the “flexible mechanisms” [UNFCCC, 2008c] does give special attention to the issue of cost efficiency in reaching national targets.

As already described above, economic competition may limit national governments in legally prescribing emission reduction options. As an alternative to legally prescribing reduction options, governments may stimulate industry to embrace voluntary agreements [European Commission, 1996]. Such agreements usually allow industry to find the lowest cost options, and thus also focus on cost efficiency. By following the market in finding the least cost options, governments avoid making a fundamental choice between different technological options and leave such choices to the market. Porter and Van der Linde [1995] argue that this view of competitiveness is flawed because of the negligence of dynamics in such assessments. They discuss how properly designed environmental standards may enhance competitiveness in a dynamic business environment, rather than damage it. This chapter does not take a position in the discussion on the environmental effectiveness of voluntary agreements (see eg. [EEA, 1997]). Compared to “command and control” instruments, voluntary agreements lead to additional uncertainty for stakeholders, e.g. regarding compliance of other stakeholders [Dawson and Segerson, 2008], and the development of prices and reduction technologies. Still, voluntary agreements may increase the number of reduction options available to individual stakeholders, which may stimulate perceived control. Moreover in case of sectoral agreements, these instruments may decrease the number of stakeholders, and specifically group identity, involved in reaching a target.

2.8. Policy boundaries: Domestic targets versus compensation mechanisms

The location of emissions leading to climate change or to ozone depletion is usually considered irrelevant to their ultimate effect. By setting domestic targets for emissions, national governments claim responsibility for their part of global emissions. In the Montreal Protocol, national governments committed themselves to strict domestic targets: the limits to domestic production and consumption are non-flexible. In the Kyoto Protocol, a different approach is followed. Although each Annex I country has accepted a responsibility to limit their emissions, countries are allowed to compensate a domestic overshoot through the series of “flexible mechanisms” [UNFCCC, 2008c]. These mechanisms allow countries to compensate an innate difference in the ability to achieve their target, and serve to level marginal abatement costs throughout Annex I; countries which have only more expensive domestic options for reductions, e.g. because they already have a fairly energy (or carbon) efficient society, may look for reduction options elsewhere. However, by including these options, the group of available reduction options that are involved in reaching a “domestic” target is expanded with options from abroad. Because the “Clean Development Mechanism” allows compensation even through reduction options outside of the Annex I territory, the group of processes is increased even beyond the processes initially involved in the overall Kyoto target. Theoretically these mechanisms include every process that is emitting GHG throughout the world. Obviously, for the individual stakeholders involved in climate policy, most of these additional reduction options add only one response option (to compensate their emissions instead of reducing them) while the mechanisms significantly increase the total number of reduction options and thus uncertainty about which course may be the most efficient.

2.9. Discussion of the design distinctions

Given the low effectiveness of the Kyoto Protocol compared to that of the Montreal Protocol discussed earlier, the stakeholders involved in the former were clearly less motivated by climate policy to reduce GHG emission, than stakeholders in the latter were

Table 2.2 Summary of design distinctions between the Montreal Protocol and the Kyoto Protocol and their influence ("+" increase, "-" decrease) on the number of stakeholders involved, available reduction options, and the level of uncertainty in the Kyoto Protocol. The number of reduction options is differentiated in total number of options (T) and number of options available to individual stakeholders (I).

	Montreal Protocol	**Kyoto Protocol**	**Influence on number of stakeholders, options and uncertainty in the Kyoto Protocol**			
			Stake-holders	Options		Uncer-tainty
				T	I	
Policy Object	Source	Effect		+		
	Categories of gases	Basket of gases	+	+		
Policy Goal	Elimination	Reduction		+	+	+
	Path and Final	Temporary				+
Policy instruments	Command and control	Market Mechanism		+	+	+
	Uniformity	National Differentiation	-			-
	Purely domestic	Compensation	+	+		

motivated by ozone policy to reduce ODS consumption and production. This chapter presents a comparative assessment of the design distinctions between both protocols that may help to explain this difference in effectiveness.

Table 2.2 summarizes the design distinctions between the Montral Protocol and the Kyoto Protocol and their influence on the number of stakeholders involved, available reduction options, and the level of uncertainty in the Kyoto Protocol. The assessment shows that the policy design in the Kyoto Protocol and the Montreal Protocol differs at various levels. It shows that many of these design distinctions lead to the Kyoto Protocol having a larger number of stakeholders involved, a larger number of possible emission reduction options, and larger uncertainty for the involved stakeholders compared to the Montreal Protocol, even without counting the multitude of processes leading to GHG emissions compared to those of ODS emissions.

In order to be able to assess the opportunities for improving the climate regime, a distinction should be made between design distinctions resulting from intrinsic differences and distinctions for other reasons. The chapter assumes that distinctions resulting from intrinsic differences offer little opportunity for improvement. However, distinctions for other reasons may be regarded as the result of (deliberate) political choices that might also be made differently. Below, the interplay of intrinsic differences and (non-intrinsic) policy choices is discussed.

The objective to control the effect of processes rather than to eliminate the sources may be explained by the (intrinsic) impossibility to eliminate all the sources of GHG emissions. In practice, most policy measures still aim at targeting the GHG source of processes, although the effects oriented principles of carbon capture and storage as well as (re)forestation seem to be getting more attention recently. However, this intrinsic difference does not explain why processes for which alternatives have been found, are not facing elimination, similar to ODSs in the Montreal Protocol.

In principle, each process provides opportunities to reduce GHG or ODS emissions; processes can be either made more efficient, or eliminated. In the Montreal Protocol a clear choice is made to ultimately eliminate all processes that involve ODS. Given society's dependence on processes resulting in GHG emissions, eliminating all processes that result in GHG emissions is hard to conceive, even if only anthropogenic processes were involved. However, this does not mean that no elimination could occur; some processes may well be eliminated, while others continue. A differentiation in approach, e.g. by substance or by sector, is not prescribed by the Kyoto Protocol; all processes are aggregated in a cumulative target. In contrast, the Montreal Protocol does differentiate its approach of different categories of ODS by setting differentiated phase-out schedules, even though its ultimate aim of elimination is generic. This absence of a clear political choice in the determination of the sectors or substances in which (and how much) to realize emission reduction should be regarded a non-intrinsic distinction between the Montreal Protocol and the Kyoto protocol; ultimately it is a political decision to delegate the responsibility through market mechanisms. However, the intrinsic difference in perceived urgency between the issues of ozone depletion and climate change, and the resulting difference in built capacity for policy measures should not be neglected. Considering the high economic stakes that are involved in processes that lead to GHG emissions, restrictions of a command and control type, similar to those suggested by the Montreal Protocol, are much less politically feasible in preventing climate change. Achieving the highest possible economic efficiency may be seen as an approach to deal with this lower capacity in the Kyoto Protocol.

The absence of an ultimate goal in the climate regime may be one of the largest sources of uncertainty for stakeholders. The restricted time span of the Kyoto target makes the long term pay-off of investment decisions questionable and thus may be regarded as a cause for stakeholder inaction. Although a higher uncertainty exists in the cause-effect relations for climate change than for ozone depletion, the absence of a future target may be regarded a deliberate choice, especially given that a target could always be adjusted both upwards and downwards.

The difference in delegation of global responsibility to national governments is partly theoretical. In principle, individual countries are able to choose their own policy under both the Kyoto Protocol and the Montreal Protocol. The ultimate goal of the Montreal Protocol however leaves little space for national ozone policies other than elimination, which makes international policy more or less uniform. National climate policies are not "fixed" in such a way by the Kyoto Protocol, although the risk for countries' or companies' competitive positions may restrain deviant unilateral national policies. This difference between the Kyoto protocol and the Montreal protocol may thus also be regarded the result of policy design choices.

Lastly, the introduction of the flexibility mechanisms may be regarded as a purely deliberate choice, in line with the earlier noted aim of achieving highest possible economic efficiency. There is no obvious intrinsic difference that necessitates this design difference.

In summary, the intrinsic differences between ODS and GHG and between ozone depletion and climate change result in more stakeholders, a higher total number of reduction options with only limited additional response options for individual stakeholders, and more uncertainty involved “naturally” in climate policy. Our comparative assessment of the Kyoto Protocol and the Montreal Protocol finds that, next to design distinctions related to intrinsic differences, several non-intrinsic policy design distinctions further increase the number of stakeholders, total number of reduction options and uncertainty, mainly for reasons of economic efficiency. As discussed in section 2.3, the literature from game theory, social sciences and policy sciences, suggests that these issues may lead to less cooperation by individual stakeholders and thus to lower policy effectiveness, which seems to be corroborated by the lower effectiveness of climate policy compared to that of ozone policy.

Addressing responsibility in the current climate policy seems much more difficult than in the ozone policy. Scientific uncertainty about the costs and effects of the multitude of possible reduction options, for a multitude of gases, in a multitude of stakeholder sectors, makes finding the measures with lowest marginal abatement costs difficult. Additional uncertainty is caused by the absence of future policy targets, which makes investment decisions more difficult for stakeholders. The absence of strict rules or preferences means that stakeholders that act risk competitive disadvantage compared to competitors that do not act. All these uncertainties may make many individual stakeholders hesitant to take action, and wait for more clarity.

2.10. Considerations for a future climate regime

Negotiations on a future climate regime are currently ongoing. These negotiations aim at agreement to drastically reduce global emissions by 2050 [UNFCCC, 2008a]. Undoubtedly, this future target will require much more effort from the stakeholders involved than the current target. Given our findings, a future climate policy’s effectiveness may increase by strengthening its effects on stakeholders’ motivation to cooperate.

Hauert et al. [2006] list several mechanisms that may increase cooperation in common dilemmas. One of these is the possibility to punish noncooperation, which is shown to increase cooperation [Fehr and Gächter, 2000]. However, effective sanctioning is a delicate issue in international policy, since it infringes national sovereignty. The non-compliance procedures in Montreal and Kyoto do not aim at the individual stakeholders, but aim at the national governments. At the national level, there are much more possibilities for sanctioning of noncompliance. However, as discussed before, given the importance of maximizing competitive positions and providing a level playing field for international trade, countries are restricted in taking unilateral measures. Apparently, international measures are restricted by national considerations, and national measures are restricted by international considerations. Either agreeing to uniform measures on a global scale, or finding ways to enable the strengthening of domestic measures seem options to change this stand-off, and allow national government to punish domestic noncooperators.

Our assessment of design distinctions offers some handles for the design of future climate policy. To increase stakeholder cooperation, a future climate policy should reevaluate some of the non-intrinsic design distinctions that lead to larger stakeholder group size or larger uncertainty. Possible approaches to accomplish this are for instance to set sub group (e.g. sectoral or substance-based) targets and limit compensation mechanisms. Such approaches could be introduced in both international and national policy. Although it is unlikely that national governments would give up authority over national policy, a collective approach to target specifically international trade, may reduce the issue of domestic competitive positions. On a national scale, setting sectoral reduction targets may imply a shift from market mechanisms towards command and control mechanisms. However, sectoral targets could also be used as a base for market mechanisms, e.g. by defining a distribution scheme for the distribution of emission rights amongst sectors ("grandfathering"). A political preference for certain reduction options may exist for reasons of cost effectiveness, equality, national security or various other reasons. Such a political preference may be voiced in these ways, giving a clear signal to the stakeholders involved, which may increase cooperation.

Setting a sectoral target would reduce group size and may strengthen group identity, trust, and stakeholder commitment, efficacy and responsibility. Additionally, this will reduce uncertainty on the magnitude of required effort of individual stakeholders. Our research suggests that limiting the number of stakeholders involved and the level of uncertainty may lead to a more effective policy.

Our analysis further shows that many of the design distinctions lead to a larger number of available reduction options in total, but often add only limited additional response options for individual stakeholders (most notably waiting for or paying off others to realize the required emission reduction). More response options may increase motivation and perceived control for stakeholders, but only if options actually exist on an individual stakeholder level. A future policy design should therefore carefully analyze in which cases adding reduction options outweighs the loss of group identity, efficacy and trust and the higher uncertainty on investment decisions which results in case extra stakeholders are being involved.

One of the most important issues to reduce uncertainty is setting a clear pathway for future global greenhouse gas emissions. Knowing what the future will require will reduce uncertainty in the payoff of investment decisions and will define the common "resource pool", which should reduce "overextraction". The current negotiations that aim to reach agreement on such a target are therefore taking a step in the right direction.

2.11. Conclusion

The differences in the efficiencies of the Kyoto and the Montreal Protocol are often attributed to the intrinsic differences between the issues of ozone depletion and climate change. Obviously, many more intrinsic difficulties exist in resolving the climate issue than in resolving the ozone issue. However, the differences in efficiencies may be increased by policy design distinctions between both international environmental treaties. This chapter shows that many of these design distinctions between the Montreal

Protocol and the Kyoto Protocol result in a larger stakeholder group, more totally available reduction options without notably increasing individual stakeholders' response options, or increased uncertainty about the economic efficiency of reduction options for stakeholders. Larger group size, increased number of options, and higher uncertainty may lead to a higher chance of noncooperation and in turn to a lower effectiveness of the treaty.

Apart from design distinctions inspired by intrinsic differences, most other design distinctions seem to be inspired by motives of economic efficiency. Furthermore, protection of the domestic competitive position seems to restrain the possibilities for national policies. Because a future climate policy will require even higher cooperation by stakeholders, a future climate regime may want to reevaluate these motives. To increase future stakeholder cooperation, approaches that may reduce stakeholder group size, adapt the number of reduction options so that it increases individual stakeholders' motivation and that reduce uncertainty for stakeholders may be considered, such as the inclusion of sectoral or substance-based emission targets in either national or international climate policy.

3. Fluorocarbon emissions in rapidly developing China under ODS phase-out[1]

Abstract *Fluorocarbon demand in China has increased rapidly recently and is expected to increase further due to sustained economic growth. Fluorocarbons are mostly used as refrigerants and generally are potent greenhouse gases, which is why their increased use and emission in a country with a population as large as China's may be important from a global climate policy perspective. Because chlorinated fluorocarbon emissions contribute to ozone depletion, they are being phased out under the Montreal Protocol (MP). The 2007 MP amendment is expected to result in reduced future HCFC emissions in developing countries, but may result in increased HFC emissions. This study investigates how the 2007 MP amendment influences future fluorocarbon emissions, from a perspective of global climate policy. Based on several scenarios in a vintage model, it projects fluorocarbon demand and emissions in three sectors: mobile air conditioning, stationary air conditioning and refrigeration. It finds that Chinese fluorocarbon emissions may increase to the order of 0.5 – 1 Gt* CO_2*-eq annually, which suggests that refrigerant emissions in China may become of global importance. It finds that without the 2007 MP amendment, these emissions would even be about 0.5Gt CO2-eq higher, which suggests the 2007 MP amendment is very successful from a climate protection perspective. However, because the UNFCCC does not include ozone depleting substances (ODS) in its basket of GHGs, most of this success is not recognized under UNFCCC. In contrast, the study finds that in various scenarios the GHG emissions accounted for under UNFCCC are higher under the 2007 amendment than under the old MP. The study concludes that the exclusion of ODS under the UNFCCC may result in suboptimal GHG emission reduction strategies.*

[1] This chapter is based partly on a study performed at the International Institute for Applied Systems Analysis (IIASA). The full study is reported in a separate report: Hekkenberg (2007). *Baseline F-gas emission projection for China 2000-2030 for GAINS Asia.* IIASA YSSP report.

3.1. Introduction

The Montreal Protocol [UN, 1987] regulates a stepwise phase-out of the production and consumption[2] of ozone depleting substances (ODSs) in industrialized and developing countries. Different categories of substances have different phase-out schemes. Moreover, the schemes differ between industrialized countries and developing countries, allowing a longer consumption of ODSs in developing countries. In industrialized countries, CFC consumption is already fully phased out; CFCs are still in use in various applications, but no new CFCs may be purchased to substitute losses from applications. Consumption of HCFCs is restricted to 65% of the baseline since 2004, with a reduction step to 25% of the baseline coming up in 2010. In developing countries, CFC consumption is to be fully phased out in 2010. HCFC restrictions start in 2013, with stepwise phase-out until 2040. The phase-out steps for HCFCs in developing countries were specified in the most recent amendment to the Protocol[3] which was agreed to in 2007. The main reason for the 2007 amendment was that HCFC use in especially China was developing very rapidly [UNEP, 2007b], possibly delaying the restoration of the ozone layer. Moreover, faster and earlier phase-out of HCFCs was also thought to reduce their contribution to global warming, since most HCFCs (like CFCs) are potent greenhouse gases [Velders et al., 2007]. China is currently the world's largest consumer of HCFCs [UNEP, 2007b]. Its population size of 1.3 billion makes it the world's largest emitter of GHGs even at its current developmental state. Its projected sustained rapid economic growth is expected to further increase its global contribution to climate change. It therefore forms a crucially important country in addressing resolving climate change.

Table 3.1 HCFC phase-out schemes for developing countries in the 1999 and the 2007 amendment to the Montreal Protocol *The production and consumption after 2030 is allowed for servicing only*

	Freeze date	Baseline	**Allowed consumption compared to baseline** 2013	2015	2020	2025	2030	2040
1999 Amendment	2016	Average production or consumption of HCFC in 2015		100%				0%
2007 Amendment	2013	Average production or consumption of HCFC in 2009/2010	100%	90%	65%	32.5 %	2.5% *	0%

[2] ODS consumption under the Montreal Protocol is defined as the amount of ODS produced in a country plus the amount imported minus the amount of ODS exported. Production and consumption limits are generally equal, except for a limited amount of additional production allowed in industrialized countries to export to developing countries.

[3] The original Montreal Protocol (1987) was subsequently amended in 1990, 1992, 1995, 1997, 1999 and 2007

Compared to the earlier amendments to the Protocol the phase-out steps for HCFCs form a clear improvement. The baseline on which the future consumption level is based is reduced from the level in 2015 to the average of the 2009 and 2010 level, the 'freeze date' at which restrictions formally start is moved forward from 2016 to 2013. Finally, phase-out steps are introduced that reduce the allowed consumption levels firmly before the ultimate phase-out date of 2040 (see Table 3.1).

HCFCs have been and are still widely used in refrigeration and air conditioning systems. Historically, refrigeration and air conditioning systems mainly used CFCs as refrigerants and as foam blowing agents in insulating foams. In general over the life time of refrigeration and air conditioning systems, refrigerant emissions are much higher than blowing agent emissions, therefore this study focuses on refrigerant emissions. The phase-out of CFCs led to partial substitution by HCFCs in various sub sectors. In industrialized countries, the subsequent phase-out of HCFCs has led to a second wave of substitution by HFCs and other substances. In some sectors, such as in mobile air conditioning, CFCs were replaced by HFCs directly. A similar development may be expected in developing countries when HCFC phase-out starts from 2013 onwards.

Like CFCs and HCFCs, many HFCs are potent greenhouse gases. HFCs are included as one of the 6 (groups of) GHGs accounted for in the UNFCCC[4] [UN, 1992b] and the Kyoto Protocol[5] [UN, 1997]. Current HFC emissions account for approximately 1% of global GHG emissions and occur mainly in industrialized countries [IPCC and TEAP, 2005]. The upcoming phase-out of HCFCs in developing countries, combined with their rapid economic development may lead to a sharp increase of substitute HFC emissions in such countries. The increasing use and emission of HFCs in refrigeration and air conditioning systems give rise to concern from the perspective of climate change mitigation.

Thus, the HCFC phase-out is expected to result in declining global warming effect from HCFC emissions and an increasing effect from HFCs. The contribution of each of these effects will determine its balance [Velders et al., 2007]. Moreover, since CFCs and HCFCs are not included in the UNFCCC (because they are already controlled through the Montreal Protocol), the perceived balance may also depend on the accounting perspective. However, whether accounted for in political agreements or not, all emitted greenhouse gases ultimately contribute to global warming. A proper accounting of emissions from refrigeration and air conditioning and the effects of the HCFC phase-out should thus include the global warming potential of decreasing HCFC emissions.

Additionally, since HCFC consumption in developing countries is expected to grow before its phase-out starts, its contribution to global warming may be a reason for concern in itself.

3.2. Aim

The principal question that this chapter addresses is 'What consequences does the 2007 Montreal Protocol amendment have for the global warming potential of fluorinated refrigerant emissions from refrigeration and air conditioning systems in China?'.

[4] United Nations Framework Convention on Climate Change

[5] UNFCCC and the Kyoto Protocol cover CO_2, CH_4, N_2O, HFCs, PFCs and SF_6

In order to answer this question, the study roughly estimates the emissions from the Chinese refrigeration and air conditioning sector from 1990 to 2030. This period enables a look beyond the HCFC freeze date and encompasses all steps of the HCFC phase-out scheme for developing countries.

This study investigates the global warming potential of expected HCFC and HFC emissions from mobile air conditioning (MAC), stationary air conditioning (SAC) and an aggregated group of refrigeration (REF) including industrial and commercial refrigeration. The study compares the projected emissions in case of the current (2007) Montreal Protocol with projected emissions under the previous (1999) Protocol. A rigorous assessment of future emissions is not within the scope of the study; rather, it aims to indicate the magnitude of emissions from the R+AC sector in this globally important developing country, in order to roughly assess the effect on global warming of the 2007 Montreal Protocol amendment. Moreover, it aims to show how the political agreement to exclude ODSs under UNFCCC and the Kyoto Protocol leads to large differences between actual and accounted emissions.

3.3. Methodology

A vintage model is constructed to project the future fluorinated refrigerant stock in each of the three sectors. Vintage models can track the growth of the number of systems by adding yearly growth and subtracting yearly disposal of obsolete systems. In a first approximation, emissions from refrigerant leakage are assumed to be linearly related to the amount of fluorocarbons contained in the systems and emissions from disposal are assumed to be linearly related to the amount of fluorocarbons in the disposed systems. Because of differences in data availability and in the expected influence of the MP amendment on emissions, the methodological approach to calculate emissions differs between MAC systems and REF and SAC systems. The following sub sections further clarify the methodology followed to estimate emissions from MAC, REF and SAC systems.

3.3.1. MAC systems

Chinese MACs used to contain mainly CFC-12. However, more recently, the share of HFC-134a systems is larger [IPCC and TEAP, 2005]. From 2010 onwards, the use of CFCs was already to be totally phased out under the 1999 Montreal Protocol. The 2007 MP amendment is thus not expected to alter the future emissions from MAC systems. Still, MAC emissions form an important source of fluorocarbon emissions in industrialized countries. The projection of MAC emissions in China is carried out to complement the overview of fluorocarbon emissions from the R+AC sectors in China.

For reasons of simplification, the assessment assumes all MAC systems to be HFC based. Given the relatively small number of cars (and consequently MAC systems) currently in use compared to expected future car numbers, this assumption is expected to have only minor influence on future emission estimates. The Chinese Energy Research Institute (ERI) has estimated future car numbers until 2030 for the GAINS-Asia database [IIASA, 2007]. Their estimation is used to calculate the number of newly produced cars in a vintage model. The model calculates the number of additional cars required to reach the estimated car numbers and the number of cars that is discarded after its lifetime. In the model, car lifetime is assumed to be 15 years. The total number of cars with MAC systems in use can be calculated by estimating the share of new cars equipped with MAC systems.

The share of new cars equipped with MAC is assumed to gradually increase from 50% in 1995 to 90% in 2020 and remain constant afterwards. Hafner and Nekså [2006] state that most new cars in China are fitted with a MAC system. Each system is assumed to be charged with 0.67 kg of HFC-134a [Tohka, 2005]. Emission rate is estimated to be 15% of the charge per year; resulting emissions are presumed to be replenished annually. The remaining charge at end of life (90% of full charge) is supposed to be fully emitted at disposal. Thus, over a system's lifetime, 3.15 times its original charge is emitted, which falls between Hafner and Nekså's optimistic and worst case estimate. The refrigerant currently used in MAC (HFC-134a) has a GWP of 1430. Multiplying the weight of emitted substance by this value results in the total CO2eq tonnage of emissions.

3.3.2. REF and SAC systems

Estimating stocks and emissions from SAC and REF systems is less straightforward due to limited consistent data availability on the number of systems in use currently and in the future. Therefore, for both SAC and REF systems, emissions under the most recent and the previous version of the Montreal Protocol are each projected in four scenarios that estimate the uncertainty range through.

The number of systems in operation throughout the world is largely unknown; therefore the estimation of stocks and related emissions can only be estimated roughly and indirectly. In this approach, the use of fluorocarbons is used as a proxy for REF and SAC system demand. Generally, fluorocarbons in these sectors may be used to fill newly built systems or to replenish leakages in existing systems. An estimation of stock build-up thus requires estimating the share in consumption of these uses.

UNEP [2008] reports the annual consumption of HCFCs, which are used to estimate stock build up until 2004.

These stocks, as a proxy for demand for REF and SAC systems, are assumed to parallel projected economic growth. In order to estimate an uncertainty range of possible future demand, a high growth scenario and a medium growth scenario are assessed. These scenarios are based on two available growth projections; ERI [IIASA, 2007] (high growth) and IEA [2007, pg 62] (medium growth), which are presented in Table 2. It should be noted that any projection of economic growth is surrounded by large uncertainties. At the time of calculation, the medium growth scenario was thought to represent a conservative estimation. In the light of economic developments after the projection dates, even the medium growth scenario may estimate growth too optimistically.

Table 3.2 Annual growth rates in GDP in the different growth scenarios.

	2000	2005	2010	2015	2020	2025	2030
IEA (medium growth)	7,70%	7,70%	7,70%	7,70%	4,90%	4,90%	4,90%
ERI (high growth)	11,64%	11,64%	9,91%	8,62%	7,62%	6,67%	5,74%

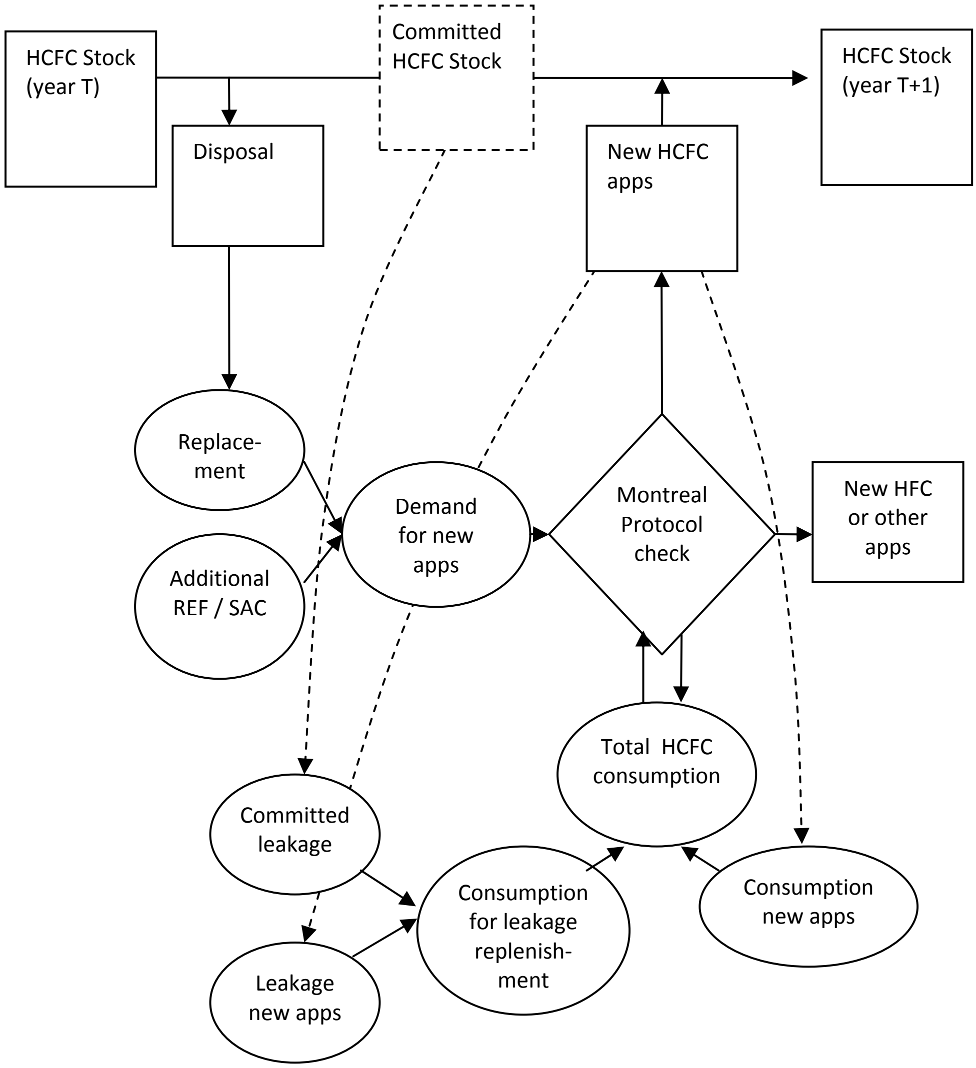

Figure 3.1 Graphical representation of the calculation module to calculate the share of REF and SAC demand that can be met by HCFCs and the share that needs to be met by other means (HFC or other). Rectangles represent actual REF or SAC applications in use. Arrows represent the directional relations between different calculation steps. Note that a recursion exists in calculating the new HCFC applications which is resolved by adding the expected emission from new applications to the amount of HCFC that is required for each new application.

Nonetheless, the differences between the scenarios clarify the consequences of different growth rates on future emissions from REF and SAC systems. Through this approach the demand for REF and SAC systems is calculated from 2005 to 2030, which forms the base for the further calculation of the consumption and emission of fluorocarbons (see below).

The limits for consumption of chlorinated fluorocarbons imposed under the Montreal Protocol (see Table 3.1) impair continuation of 'business as usual' after the freeze date. In the hypothetical business as usual scenario demand for REF and SAC systems is assumed to be fully met by HCFC systems. In the projected scenarios, demand for REF and SAC systems that cannot be met by HCFC-based systems due to the MP restrictions is assumed to be met by HFC-based and other systems. Figure 3.1 shows the modeling approach that is used to assess the demand that can be met by HCFCs and the demand that should be met by other means, including by HFCs. Based on total demand for REF and SAC systems, the build up of HCFC stocks is estimated from year to year. Since systems are estimated to last 15 years, the built up stock predetermines a (large) part of expected emissions in the future. The model assumes that emissions from leakage are replenished each year. Thus, stock build up and emissions predetermine a part of the consumption in years to come. Comparing this *committed* consumption with the allowance under the MP, results in the available remaining consumption allowance that can be used to install new systems.

For each growth scenario HFC consumption (and related emissions) is calculated in a low and a high substitution scenario, so that the uncertainty range for REF and SAC emissions under the 1999 and 2007 MP amendment is described by the range between the four scenarios (2 different growth rates, 2 substitution rates). HFC emissions are complemented by emissions of HFC-23 as a byproduct of HCFC-22 production. In the assessment, no waste gas treatment is assumed to be implemented, even though such treatment forms one of the main project activities in the Clean Development Mechanism (CDM). This assumption will be further discussed in the discussion.

Finally, the amounts of HCFCs and HFCs that are emitted in each scenario are converted to CO2-equivalents by estimating the average GWP of the mix in use in order to enable comparison. As noted in the introduction, the global warming potential of HCFCs is not accounted for in the Kyoto protocol. Thus, the implications of substituting HCFCs by HFCs may be perceived differently when Kyoto accounting rules are observed. In a final assessment, the difference between Kyoto accounting and comprehensive accounting is analyzed by comparing the effect of the 2007 MP amendment on emissions including and excluding HCFCs' GWP.

3.3.3. Assumptions and estimations.

The approach described above requires various assumptions and estimations for fluorocarbon consumption, emission and practices.

UNEP provides data for historic CFC and HCFC consumption on a country level. Chinese consumption in 2004 amounted to 17.9kt of CFC and 10.4kt HCFC measured in ODP-equivalents [UNEP, 2008]. To convert these numbers to metric tons of fluorocarbons, conversion factors of 1 (CFC-11, ODP 1) and 18 (HFCF-22, ODP 0.055) were used and resulted in a total of roughly 200kt fluorocarbon consumed in 2004. Data from [IPCC and TEAP, 2005] can be used to estimate the share of fluorocarbon demand used in different sectors in developing countries. From these data, REF appears to lead to 64% of total fluorocarbon demand whereas SAC leads to 18% of demand. Thus, the amount of fluorocarbons consumed in 2004 in China for SAC is estimated at roughly 38kt and the amount of fluorocarbons for REF is estimated at roughly 130kt.

The shares of consumption used for emissions, replacement of disposed systems and new demand can be calculated from emission rate, lifetime and stock growth rate (see box 3.1). The growth rate is calculated from the historic growth of fluorocarbons demand between 1990 and 2004, which equaled 12% annually. Lifetime and emission rate are

Box 3.1

Because historic stock build-up is unknown from consumption figures, the calculation of the shares of stock buildup, emission replenishment and disposal replacement in total fluorocarbon demand requires some mathematical modeling. We have constructed a mathematical model to represent the evolvement of fluorocarbon stocks, emission and disposal with the following set of formulas.

If we assume exponential growth, the stock of fluorocarbons in applications at each time is represented by

$$STOCK_T = STOCK_0 * (1+GR)^T \qquad \text{(B1)}$$

Emissions can then be formulated as

$$EM\_USE_T = EF * STOCK_T \qquad \text{(B2)}$$
$$= EF * STOCK_0 * (1+GR)^T$$

If we assume emissions are replenished yearly, the total demand for fluorocarbons is defined by

$$DEM_T = EM\_USE_T + NEWAPP_T \qquad \text{(B3)}$$

Fluorocarbon demand for new applications depends on stock growth and replacement of disposed applications. We assume all disposed applications are being replaced by new ones, without recovery of charge

$$NEWAPP_T = ST\_INC_T + DISP_T \qquad \text{(B4)}$$

Of which stock growth can be calculated as

$$ST\_INC_T = STOCK_T – STOCK_{T-1} = STOCK_0 * GR * (1+GR)^{T-1} \qquad \text{(B5)}$$

The amount of disposal depends on the amount of fluorocarbons that was put into new applications one lifetime earlier

$$DISP_T = NEWAPP_{T-LT} \qquad \text{(B6)}$$

This creates a recursion, as disposal depends on new applications, and new applications depend on disposal. Substitution leads to an infinite summation of arguments that, for T going to infinity and GR>0 can be recalculated as

$$NEWAPP_T = STOCK_0 * GR * (1+GR)^{T-1+LT} / ((1+GR)^{LT} -1) \qquad \text{(B7)}$$

and

$$DISP_T = STOCK_0 * GR * (1+GR)^{T-1} / ((1+GR)^{LT} – 1) \qquad \text{(B8)}$$

Through these formulas we can include unknown historic stocks to our disposal calculation, and thus calculate the shares of EM_USE, DISP and ST_INC in total demand. For T going to infinity in our model, these shares are constants depending only on GR, EF and LT and can be defined as

$$SH_{DISP\ in\ DEM} = GR / (((1+GR)^{LT}-1)*(GR*((1+GR)^{LT}-1)^{-1} + GR + EF*(1+GR)) \qquad \text{(B9)}$$

$$SH_{EM\_USE\ in\ DEM} = (EF*(1+GR)) / (GR((1+GR)^{LT} -1)^{-1} + GR + EF*(1+GR)) \qquad \text{(B10)}$$

$SH_{ST\_INC\ in\ DEM} = GR / (GR + (1+GR)*EF + GR* ((1+GR)^{LT}-1)^{-1})$ (B11)

In a model representation in Microsoft Excel, with realistic values for LT, EF and GR, the value for the shares approaches those calculated already after one or two lifetimes. Also, in this Excel model the formulas for shares prove to remain valid when we introduce decreasing growth rates and decreasing emission factors. The shares can thus be used to split the reported total fluorocarbon demand in our base year in a part that is used to replace emissions, a part to replace fluorocarbons in disposed applications and a part for stock increase. From (B2) we can thus easily reconstruct apparent $STOCK_T$.

$STOCK_T$ = amount of fluorocarbons in applications at time T
GR = growth rate
EM_USE_T = emissions from use at time T
EF = emission factor
DEM_T = total demand for fluorocarbons at time T
$NEWAPP_T$ = amount of fluorocarbons in new applications at time T
ST_INC_T = STOCK increase at time T
$DISP_T$ = amount of fluorocarbons in disposed applications
LT = life time
$SH_{x\_in\_DEM}$ = Share of x in DEM

derived from literature. IPCC and TEAP [2005] estimate lifetime for various systems between 9 and 15 years. For simplicity, a lifetime of 15 years is assumed for all systems in the model. Emission rates in REF are highly uncertain; various studies estimate large differences (see table 3.3). Emission rates in China are expected to be at the high end of the range, because no legislation to prevent such leakage is known as yet. An estimated emission rate of 30% is therefore used in REF. Estimates of emission rates in SAC agree more (see table 3.4); an estimated emission rate of 10% is therefore used in SAC.

With these parameters, the share of consumption used for new systems (to replace disposed systems and fulfill additional demand) in REF is estimated at roughly 30%; in SAC this is estimated at roughly 57%. Replenishing leakage accounts for 70% of REF consumption and 43% of SAC consumption. Finally, these shares enable the estimation of REF and SAC stocks in 2004 at roughly 300kt and 160kt respectively.

The principal type of HCFC used in REF and SAC systems is assumed to be HCFC-22 [AFEAS, 2004]; we assume that no other HCFC refrigerants are used. During production of this refrigerant, HFC-23 is formed as a byproduct (1-4% weight [IPCC and TEAP, 2005; McCulloch and Lindley, 2007]), which is assumed to be emitted into the air. Therefore, HCFC consumption in REF and SAC is assumed to lead to additional emissions; 3% HFC-23 byproduct emission are additionally accounted at the time of HCFC consumption, which is the average of IPCC and TEAP (2005) and slightly higher than the global average calculated by McCulloch and Lindley (2007). Refrigerants to replace HCFCs in REF and SAC are assumed to be different mixes of HFCs. Averaging aggregate IPCC and TEAP

Table 3.3 Estimates of emission factors for REF subsectors in various studies. Letters and years indicate the spatial and temporal validity for the emission projections: (E) Europe, (G) Global. IPCC and TEAP [2005] values are calculated from estimates on banks and emissions.

	Commercial	Industrial	Transport
Tohka (2005) (E)	15%	15%	20%
IPCC and TEAP (2005) (G 2002)	30.5%	16.8%	37.5%
IPCC and TEAP (2005) (G 2015)	32.9%	15.7%	38.8%
Harnisch et al (2001) (G 1996)	20%	10%	25%
Harnisch et al (2001) (G 2010)	15%	10%	20%
Harnisch et al (2001) (G 2020)	10%	10%	15%
Harnisch and Hendriks (2000) (E)	10%	10%	15%

Table 3.4 Estimates of emission factors for SAC in various studies. Letters and years indicate the spatial and temporal validity for the emission projections: (E) Europe, (G) Global. IPCC and TEAP [2005] values are calculated from estimates on banks and emissions.

Report	Emission Factor SAC
Tohka (2005) (E)	10%
IPCC and TEAP (2005) (G 2002)	9.6%
IPCC and TEAP (2005) (G 2015)	10.7%
Harnisch et al (2001) (G)	10%
Harnisch and Hendriks (2000) (G)	10%

estimations for 2015 results in an assumed average GWP of 1974 for HFCs in REF and 1517 for HFCs in SAC.

To model the switch from using HCFCs to HFC (and alternatives), assumptions need to be made that describe the share of former HCFC demand that will be met by HFCs. IPCC and TEAP [2005] estimate that 30% of CFC demand in industrialized countries has been substituted by HCFCs and HFCs; the remaining 70% of demand is assumed to be met by efficiency gains, other applications or other substances, such as natural refrigerants (HCs, NH_3, CO_2). USEPA estimates that 80% of HCFCs in developing countries will be replaced by HFCs. Although these numbers are hard to compare, they show a large possible variation in substitution rate. Two scenarios are therefore used that assume high (80%) or low (30%) substitution rates.

3.4. Results

3.4.1. Emissions from MAC

Figure 3.2 shows the projected emissions from MAC in China. It shows that emissions increase from roughly 15 Mt CO_2-eq in 2020 to roughly 39Mt CO_2-eq in 2030. The results are highly dependent on the projected car use in China. As will become clear from the projections for REF and SAC, emissions from MAC in China are expected to have only a

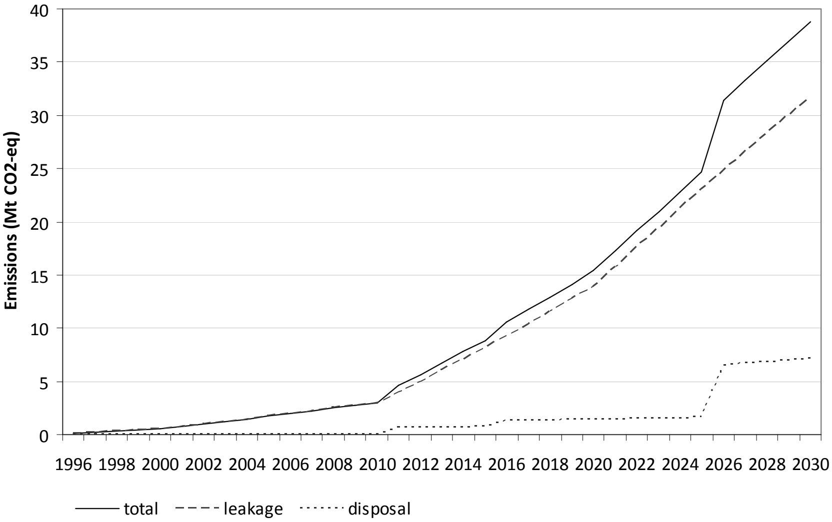

Figure 3.2 Projected emissions from mobile air conditioning leakage, disposal and total in China.

limited contribution to total emissions from the R+AC sector, thus differing from the situation in industrialized countries.

3.4.2. Emissions from REF and SAC

The described approach results in a large set of consumption, emission, stock and disposal projections. As described in the previous section, these variables are projected in four scenarios for both sectors (REF and SAC) for both versions of the Montreal Protocol (1999 and 2007). Each scenario describes either medium or high growth, and either low or high HCFC by HFC substitution. Final emissions are accounted in two ways: by accounting all emissions and by accounting only the emissions regulated under the UNFCCC. Figure 3.3 shows the emission projection for REF under the 2007 Montreal Protocol Amendment in each of the four scenarios. It projects emission from REF to develop in a range between up to 470Mt CO_2-eq and 700 Mt CO_2-eq in 2018 and between 310 Mt CO_2-eq and 1 Gt CO_2-eq by the end of the projection period (2030). SAC emissions show only a slightly different range trajectory, although with different values (Figure 3.4), ranging between 130 Mt CO_2-eq and 190 Mt CO_2-eq in 2022 and between 74 and 180 Mt CO_2-eq in 2030. The projections show that the upper and lower boundaries are formed by the high growth high substitution (HG HS) and medium growth low substitution (MG LS) scenarios respectively. Although the projected values show a wide range, the order of magnitude of projected emissions signals that emissions from REF and SAC may be expected to contribute significantly to GHG emissions in China.

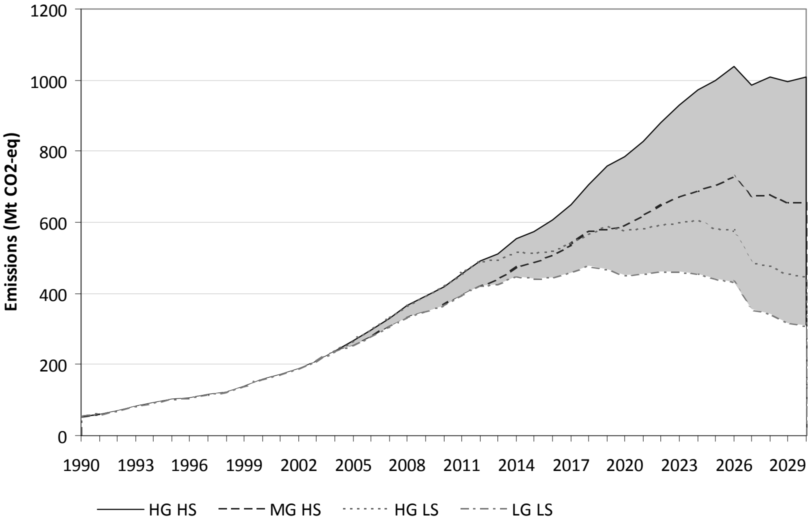

Figure 3.3 Projected emissions for REF in the medium (MG) and high (HG) growth scenario with low (LS) and high (HS) substitution ratio of HCFC by HFC under the 2007 Montreal Protocol Amendment.

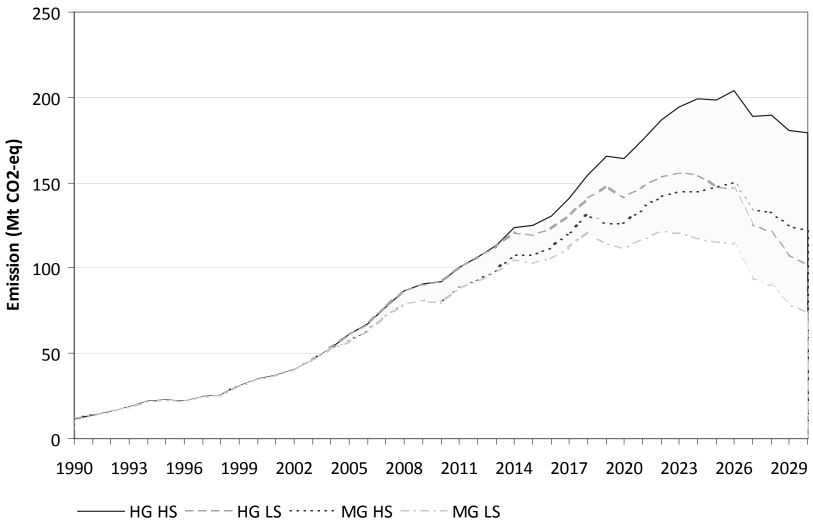

Figure 3.4 Projected emissions for SAC in the medium (MG) and high (HG) growth scenario with low (LS) and high (HS) substitution ratio of HCFC by HFC under the 2007 Montreal Protocol Amendment.

3.4.3. Comparing emissions under 1999 and 2007 Montreal Protocol

Figure 3.5 shows the resulting emission projection ranges for REF under the 1999 and 2007 Montreal Protocol amendment. It shows that the 2007 MP amendment has lead to an important downward shift of the projected emission range from 0.77-1.4Gt to 0.31-1.0Gt CO_2-eq in 2030. A similar shift is found in SAC, where the projected emission range shifts from 190-300 Mt to 74-180 Mt CO_2-eq (Figure 3.6). Comparing individual scenarios under the 1999 and the 2007 MP leads to an estimated an annual emission reduction of roughly 340-570 Mt CO_2-eq in REF and 100-150 Mt CO_2-eq in SAC in 2030. The amendment reduces cumulative emissions from SAC by 720 Mt – 1.2 Gt and cumulative emissions from REF by 2.4-5.2 Gt up to 2030.

The profiles for REF and SAC are relatively similar, although as noted the emissions from REF are much larger than the emissions from SAC. The figures show that the 2007 MP leads to a plateau in emissions in both REF and SAC, and a subsequent decrease of GHG emissions after the freeze date, rather than a continuous increase. It should be noted though that in a continuous growth scenario emissions will increase again after the projected period, due to continuously increasing HFC emissions. Nonetheless, the recent amendment of the MP is shown to lead to important emission reductions from the SAC and the REF sector.

Note that although the ranges for the 1999 and 2007 MP projections overlap, the reduction of emissions due to the implementation of the 2007 MP amendment is robust; each individual scenario leads to lower emissions in the 2007 MP than in the 1999 MP. Scenarios that result in relatively low emissions in the 1999 MP projection range also result in relatively low emissions in the 2007 MP projection range.

Figure 3.7 and Figure 3.8 clarify the emission difference between the 1999 and 2007 MP amendment by showing, for one of the scenarios (medium growth, low substitution), the build up of the emission total from emissions related to the use of HCFC-systems (including the byproduct HFC emission) and the emissions related to the use of HFC-systems. The profiles for REF and SAC are relatively similar, although as noted the emissions from REF are much larger than the emissions from SAC. Figures 7 and 8 show that the shares of emissions related to HCFC-use and HFC-use differ between the REF and the SAC sectors. HFC emissions make up a larger share of the total emissions in REF than in SAC in both the 1999 and the 2007 MP versions. This results from the higher average GWP of the HFC refrigerant mix in REF and from the higher emission rate in REF. Due to the higher emission rate, a larger part of the remaining consumption allowance is used for replenishing leakage emissions, thus leaving a smaller amount for new HCFC systems. Therefore, substitution of HCFC systems by HFC systems is projected to be faster in REF than in SAC, consequently leading to relatively more HFC emissions from REF.

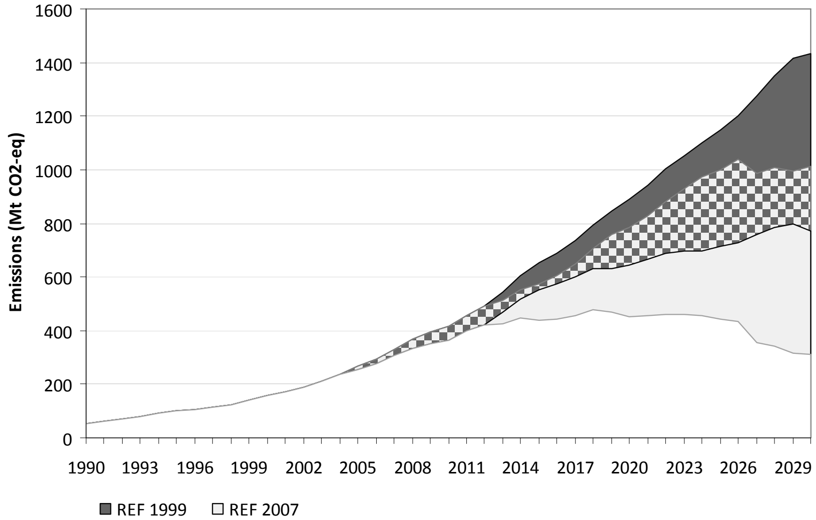

Figure 3.5 Projected emission ranges for REF under the 1999 and 2007 Montreal Protocol amendment. The overlapping parts of the ranges are checkered.

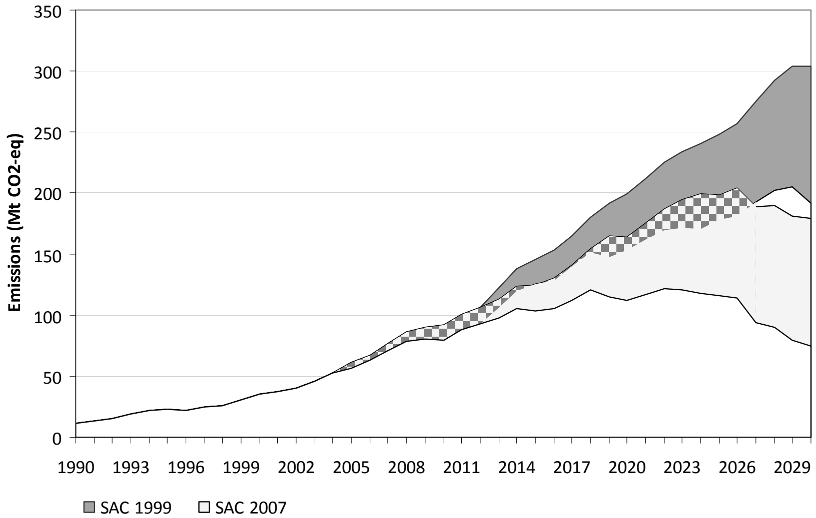

Figure 3.6 Projected emission ranges for SAC under the 1999 and 2007 Montreal Protocol amendment. The overlapping parts of the ranges are checkered.

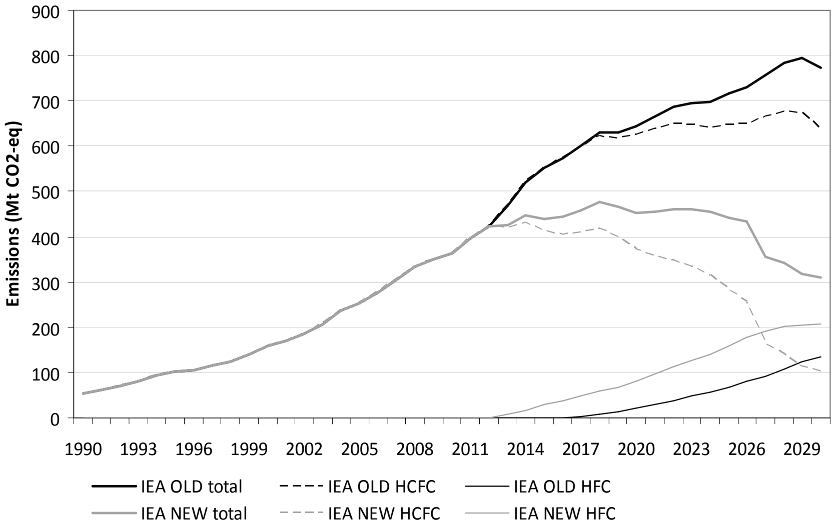

Figure 3.7 Projected emissions from REF related to HCFC, HFC and in total under the 1999 and 2007 Montreal Protocol amendment in the medium growth low substitution scenario (MG LS).

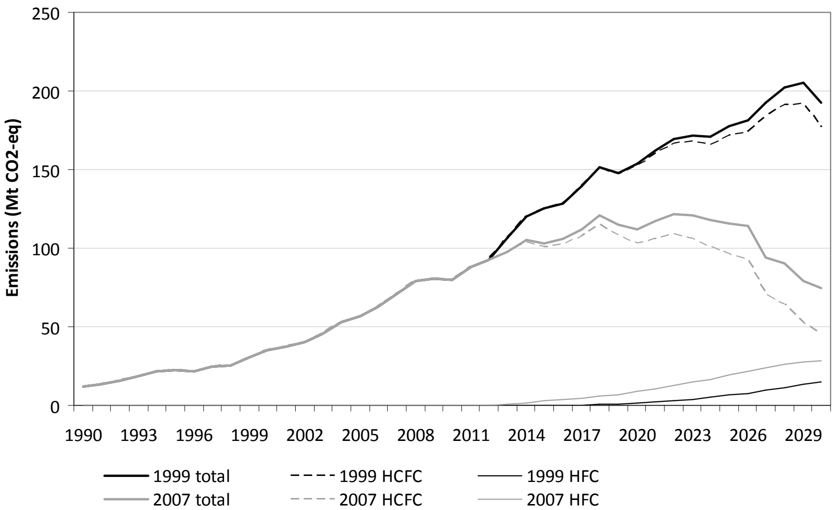

Figure 3.8 Projected emissions from SAC related to HCFC, HFC and in total under the 1999 and 2007 Montreal Protocol amendment in medium growth low substitution scenario (MG LS).

3.4.4. Comparing scenario sets

The ranges described above result from the different assumptions in each of the scenarios. This part of the result section compares the differences between the individual scenarios in order to better understand the effects of possible developments, which may occur naturally or be induced by policy intervention. Such comparison may show the effects of changes in growth rate, substitution factor and accounting method. Moreover, the relative differences between REF and SAC may show the effect of different emission rates and a different mix of substitution substances. Scenarios are therefore grouped in sets of two that differ in one assumption only so that the differing assumptions can be discussed separately. Because the effects of the discussed differences are similar across most sets of scenarios, the differing assumptions are generally presented for one set of scenarios only. Afterwards, the effects of some combinations of differing assumptions are discussed.

Note that the discussed scenarios do not show uncertainty ranges because each scenario projects one specific development only. None of the scenarios should therefore be assessed on its absolute values, but rather on its relative values and the development of its emission trajectory in time.

Growth rate

Figure 3.9 shows the projections for the REF sector for medium (MG) and high (HG) growth rates. It shows total GHG emissions under both versions of the MP in a 30% substitution rate of HCFCs by HFCs. The figure shows that the higher growth scenario (ERI) leads to higher emissions under both the 1999 (up to over 1000 Mt CO_2-eq) and the 2007 MP (over 600 Mt CO_2-eq). However, the trends in both growth scenarios are practically identical. Projections for SAC and for other substitution ratios show a similar picture. Thus, apart from changing the projected absolute amount of emissions, a different growth rate has limited influence on the trajectory of the projected emissions.

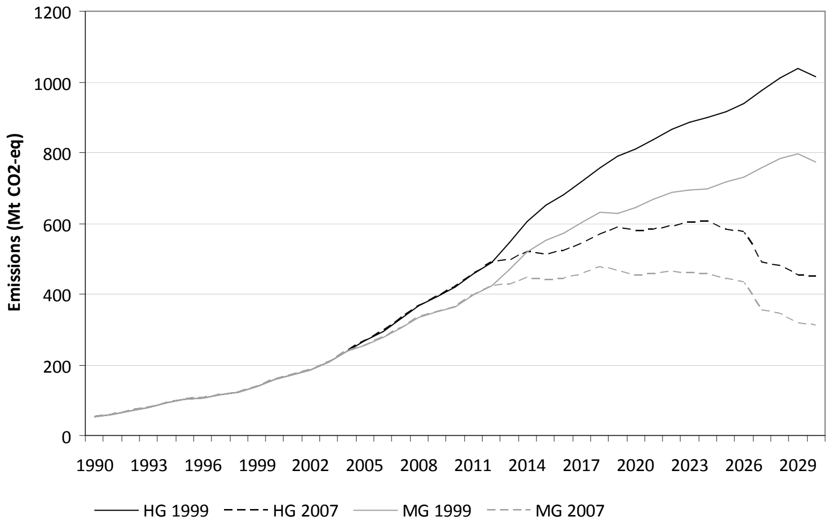

Figure 3.9 Projected emissions from REF in the medium (MG) and high (HG) growth scenario in the 1999 and the 2007 MP

Substitution rate

Figure 3.10 shows the trajectory of relative emissions from REF in the two different HCFC-HFC substitution scenarios. It shows that high substitution rate (80%) of HCFCs by HFCs lead to higher future emissions, as could be expected. It shows that high substitution results in continuous emission increase after the freeze date, whereas low substitution leads to leveling off and a decline as noted before.

Comparison of the REF scenarios with the SAC scenarios shows notable differences in their relative trends (Figure 3.11). It shows that under the 2007 MP the relative emissions of REF80 are higher than the relative emissions of SAC80, mainly due to a higher average GWP of HFCs in REF than in SAC; however, the relative emissions of REF30 are lower than the relative emissions of SAC30. Thus, a lower substitution rate in REF leads to a larger relative emission reduction in REF than in SAC. This effect is due to the higher emission rate in REF. The higher emission rates in REF lead to higher emissions, which thus consume a larger share of remaining consumption space under the MP. Therefore, less REF demand can be fulfilled by HCFC systems. Consequently, a larger share of demand needs to be met by alternatives and these alternatives make up a larger part of total emissions in REF. Decreasing the share of this demand for alternatives that is met by HFCs thus leads to larger relative emissions reductions.

'UNFCCC accounting'

Figure 3.12 shows the projected range of emissions from REF in the 1999 and 2007 MP when accounting only the UNFCCC gases and compares these ranges with the ranges when accounting all fluorinated gases as in figure 4. It shows that the exclusion of HCFCs in the UNFCCC accounting leads to a massive underestimation of real global warming effects, as might be expected. A similar underestimation occurs in the SAC projection (not shown). It should be noted that until the freeze date, the UNFCCC accounting only consists of the HFC-23 byproduct emission of HCFC-22 production.

Figure 3.13 to 3.16 further specify this observation by focusing on single scenarios for REF and for SAC; All scenarios assume medium growth and differ in substitution rates.

Furthermore, all figures show a clear underestimation of the beneficial climate effects of the 2007 MP amendment. Only the medium growth low substitution scenario for SAC (Figure 3.14) shows some climate benefits from switching from HCFCs to HFCs under UNFCCC accounting, because the effects of phasing out HCFC production with related byproduct emissions are projected to be larger than the increasing emissions from HFCs. In the REF scenarios and the scenarios with high substitution of HCFCs by HFCs, emissions are not projected to decrease due to the 2007 MP amendment when accounting only for UNFCCC gases. The high substitution scenarios even show an increase in emissions due to the implementation of the MP amendment when accounting only for the UNFCCC gases, contrary to the observed effects when all GHGs are accounted for. Note that high growth scenarios show comparable results.

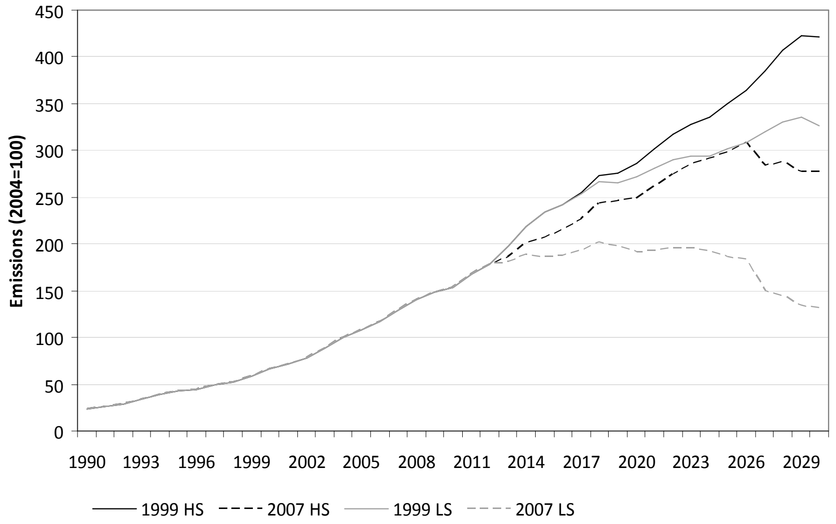

Figure 3.10 Emissions from REF in high (HS) and low (LS) substitution scenarios in the 1999 and 2007 MP

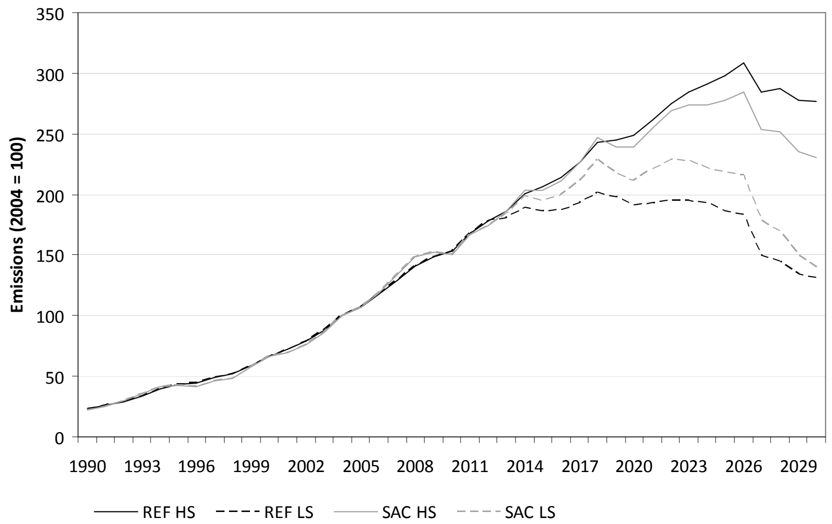

Figure 3.11 Projected relative emission in REF and SAC in high (HS) and low (LS) substitution in medium growth scenarios under the 2007 MP.

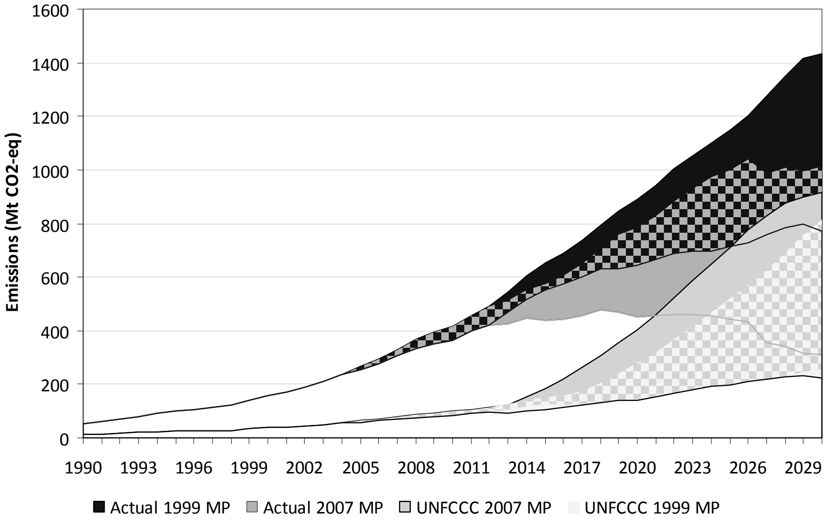

Figure 3.12 Projected emission ranges for REF under the 1999 and 2007 MP amendment using comprehensive (actual) accounting and using UNFCCC accounting.

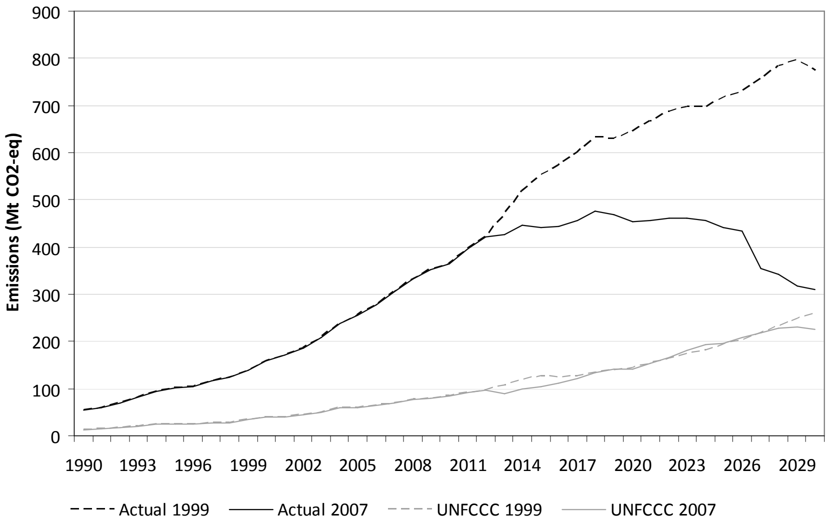

Figure 3.13 Comparison of projected 'actual' emission and UNFCCC emissions from REF under the 1999 MP and the 2007 MP in a medium growth low substitution scenario

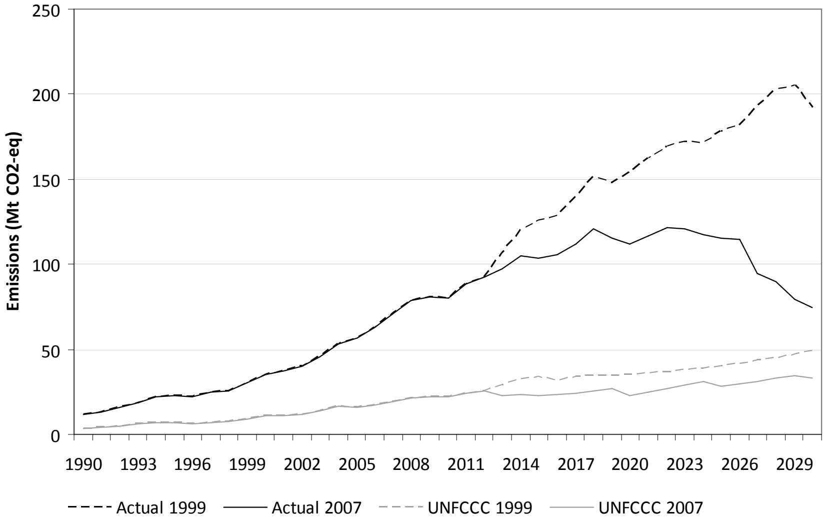

Figure 3.14 Comparison of projected 'actual' emission and UNFCCC emissions from SAC under the 1999 MP and the 2007 MP in a medium growth low substitution scenario

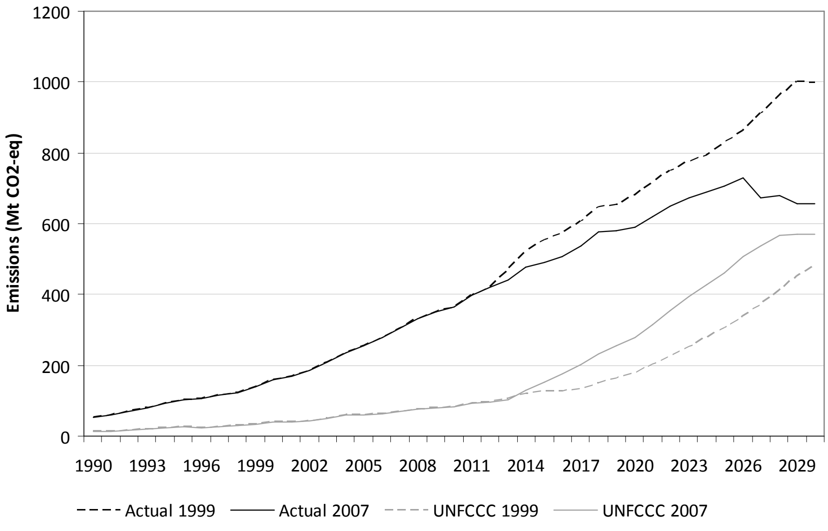

Figure 3.15 Comparison of projected 'actual' emission and UNFCCC emissions from REF under the 1999 MP and the 2007 MP in a medium growth high substitution scenario

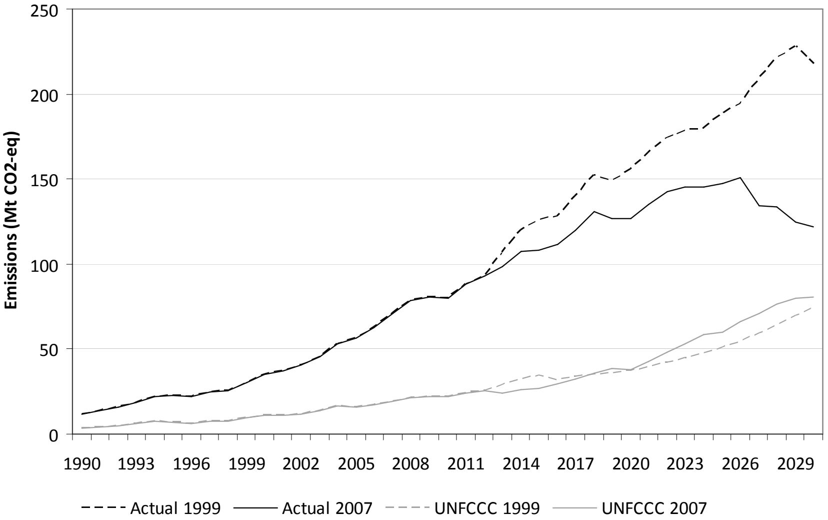

Figure 3.16 Comparison of projected 'actual' emission and UNFCCC emissions from SAC under the 1999 MP and the 2007 MP in a medium growth high substitution scenario

3.5. Discussion

3.5.1. Discussion of results

The results show that future fluorinated GHG emission from refrigeration and air conditioning in China is expected to be in the order of 0.5 – 1 Gt CO_2-eq annually in 2030. Compared to the global total annual emission (estimated at 49Gt CO_2-eq in 2004 [IPCC, 2007]), the projected emission from R+AC systems in China are thus clearly of global importance, especially given the global objective to markedly reduce global GHG emissions in order to prevent dangerous climate change. The results show that without the 2007 MP amendment, emissions would be expected to be substantially larger. The amendment reduces projected cumulative emissions up to 2030 by 720 Mt – 1.2 Gt from SAC and by 2.4-5.2 Gt from REF. The 2007 MP amendment has thus contributed significantly to reducing expected emissions.

The projections suggest that emissions from MAC are relatively limited compared to REF and SAC. Emissions from SAC and especially REF are projected to increase rapidly due to the assumed sustained rapid economic growth in China. The projected emissions from REF and SAC depend on both growth rate and substitution rate. From the projections we can deduce that both a lower growth rate and a lower substitution rate can substantially decrease future emissions. Although reducing growth rate may not be a politically interesting goal, reducing the substitution rate may form an effective goal in reducing GHG emissions. This could e.g. be pursued by stimulating non-fluorinated refrigerant or different cooling technologies in refrigeration and air conditioning. Obviously, reducing emission rates and disposal practice may also help to reduce emissions from R+AC systems. The following chapter (Chapter 4) will further investigate such reduction options.

The results further show that not accounting for HCFCs in Kyoto leads to a substantial underestimation of GHG emissions from R+AC in China. The negligence of these emissions may result in underattention for emission reduction options aimed at reducing HCFC emissions. Moreover, because UNFCCC does not include emissions of HCFCs, the benefit of the accelerated phase-out of HCFCs under the Montreal Protocol can not be marked as a success by UNFCCC, even though this phase-out will result in a substantial reduction of GHG emissions into the atmosphere over the coming years. Being able to show such success stories could have a positive influence on motivation to continue reduction efforts.

3.5.2. Discussion of methodology

It should be stressed that the projections in this study are rough approximations of future emissions. The approach used to estimate the 2004 and future stocks results in large uncertainty of future demand and thus in related consumption and emission estimations. The study investigates four scenarios which differ importantly in growth rate and substitution rate; however, the actual future development may still reach beyond the scope of the projected range. The projections are based on a continuation of business as usual; changes in emission rates, estimated life time of systems or policies that aim at reducing emissions are not taken into account. Thus the findings should be regarded as a first order approximation, in order to map the potential future environmental impact resulting from the use of fluorinated gases in rapidly developing China.

The study assumes that future demand for SAC and REF linearly parallels economic (GDP) growth. No empirical evidence for such relation exists. Assuming a different relation between demand and economic growth, e.g. one in which saturation will occur, may lead to markedly different outcomes that have not been studied. Moreover, the study has investigated only single values for emission rates and equipment lifetime, which have a large influence on projected future emissions. Smaller (or higher) emission rate and higher (or shorter) lifetime may lead to lower (or higher) annual emissions.

The study assumes that leakage will be replenisched annually. In case no such replenishment occurs, the next year's emission from the leaking application would be lower, since less refrigerant remains in the system. Thus, a lower frequency of replenishment would lead to lower overall emissions.

The study assumes that the full HCFC consumption allowance will be used. In the projection, this leads to new applications containing HCFC to be put into use for years after the freeze date. Historic data from the CFC phase-out in industrialized and developing countries and from the HCFC phase-out in developing countries suggests that actual consumption patterns may be lower than the maximum allowed. A lower HCFC consumption would result in lower total emissions, although the use and emission of HFC would be expected to be higher in such case.

Furthermore, the study assumes a lifetime of 15 years for all applications. IPCC and TEAP [2005] suggest that for some applications, this lifetime may be shorter. In the model, a shorter lifetime would result in relatively more emissions from disposal. However, a shorter lifetime would also lead to a faster phase-out of HCFC, which could lead to a lower emission estimate, due to the lower GWP of HFC replacements and due to the expected replacement by non-fluorinated alternatives. The exact effect of assuming a shorter lifetime is therefore unclear, although we may hypothesize that the more rapid phase-out would increase the difference between the projected emissions under the 1999 and the 2007 MP.

The modeling choice to calculate limits for consumption from REF and SAC separately leads to a more rapid phase-out of HCFC stock in REF than in SAC. If the total remaining consumptions allowance could be used for both types of systems, the different emission trajectories may slightly differ, due to different emission rates and different average GWP of substitution mixes in REF and SAC. Under the given assumptions, part of the allowance that is used for SAC in the current model projections would instead be used for new REF systems, thus delaying the phase-out of HCFC in REF systems and speeding the phase-out in SAC systems. Due to the higher emission rate in REF, such allowance aggregation may result in slightly higher total emissions. A phase-out policy that formalizes a separation of remaining consumption allowance could thus possibly lead to a slight emission reduction.

The model assumes that HFC byproduct emission remain an important source of GHG emissions. In actual practice, abating HFC byproduct emissions form one of the main CDM reduction options. The CDM accredits projects that prevent emissions in developing countries. The resulting credits may be used to compensate emissions in countries that have subjected themselves to emission limits under the Kyoto Protocol. Actual emission of HFC byproduct may thus be smaller than the amount projected, since much of the emissions may be abated to gain CDM credits. Still, CDM may not result in real emission reductions, but rather in a spatial and/or sectorial shift of emissions; the net effect on global emissions from these projects may be very low. After all, the emission credits created by not emitting HFC-23 in China may be used for emitting other GHGs elsewhere. It is thus debatable to which activity the achieved reduction should be counted. Moreover, CDM credits cannot be obtained for new HCFC-22 production facilities, in order not to create incentive to build new HCFC-22 production plants. It remains unclear whether such new production facilities will be equipped with waste gas destruction technology. The emissions related to HFC-23 byproduction may thus be debated. If the emissions would not be accounted towards R+AC systems, the difference between HCFC systems and HFC systems becomes smaller, but using HFC systems would still be favorable from a climate perspective.

The success of HFC-23 emission reduction as CDM option may be an example for introducing measures to abate HCFC and HFC emissions in R+AC in developing countries. CDM approved methodology AM0071 [UNFCCC, 2009a] already enables crediting a switch from HFCs to low GWP refrigerant in domestic refrigerators. Perhaps this methodology can be expanded to also include HCFC and other refrigeration and air conditioning systems in order to further reduce GHG emissions from refrigerant use. Clearly, such policy approach is only effective when the GWP of HCFC emissions is accounted for.

3.6. Conclusion

The study has investigated the emission of fluorinated refrigerants from the refrigeration and air conditioning sector in rapidly developing China from 1990 to 2030. The study concludes that such emission may form an important contribution to global GHG emissions in the future, estimated between 0,5 and 1 Gt CO_2-eq annually in 2030. This finding shows the importance of developments in developing countries in global GHG mitigation strategies. The projections suggest that emissions from mobile air conditioning are relatively limited compared to emissions from refrigeration and stationary air conditioning.

A further conclusion is that the 2007 Montreal Protocol amendment has reduced expected GHG emissions from R+AC significantly. The substitution of HCFCs by HFCs leads to lower emissions, which is magnified by the assumption that some HCFCs systems are substituted by low GHG alternatives. Strategies to increase the share of demand that is met by low GHG alternatives may contribute substantially to reducing future emissions.

Lastly, the study concludes that not accounting for HCFCs under UNFCCC may lead to significant underestimation of GHG emissions from R+AC in China. The omitting of these emissions may result in underattention for emission reduction options aimed at reducing HCFC emissions and may thus result in suboptimal GHG emission reduction strategies.

4. Exploring policy strategies for mitigating HFC emissions from refrigeration and air conditioning[1]

Abstract *The growing demand for cooling throughout the world, possibly increased by global climate change, requires the implementation of policies to mitigate the related greenhouse gas (GHG) emissions from energy and refrigerant use in the refrigeration and air conditioning (RAC) sector. This chapter aims to contribute to the discussion on strategies to reduce HFC emissions from RAC by looking at their different temporal effects, caused by stock-flow dynamics. From scenario modeling we find that containment strategies are often most effective in reducing HFC emissions in the short run, whereas phase out strategies have more potential in the long run. Further findings suggest that early and quick implementation of phase out strategies could lead to important reductions in cumulative HFC emissions, because stock build up is prevented. This timing effect is less pronounced for containment strategies. Lastly, emissions from disposal, if unabated, can lead to equally large emissions annually as those from use. Preference for several short term benefits of containment strategies might lead to sub optimal emission reduction strategies, endangering long term GHG emission reduction.*

4.1. Introduction

Refrigeration and Air Conditioning (R+AC) have been in the environmental spotlight for several decades. Where in the 80ies and 90ies policy focus was on the ozone depleting properties of the refrigerants used, this focus has gradually shifted to the sector's contribution to global warming. The ratification of the Montreal Protocol [UNEP, 1987] in 1987 and subsequent amendments have gradually moved ozone depletion from policy implementation to the enforcement stage. In the same time global attention for global warming has gradually risen, leading to the United Nations Framework Convention on Climate Change (UNFCCC) [UN, 1992b] entering into force in 1994 with near universal

[1] This chapter is a slightly adapted version of Hekkenberg and Schoot Uiterkamp (2007). *Exploring policy strategies for mitigating HFC emissions from refrigeration and air conditioning.* International Journal of Greenhouse Gas Control 1(3):298-308. doi:10.1016/S1750-5836(07)00030-8

membership[2]. Many signatories went further, and agreed to reduce the sum of their greenhouse gas (GHG)-emissions in the Kyoto Protocol [UN, 1997] that entered into force in 2005.

In the light of these international conventions, the refrigerants used in the R+AC sector have a special position. Currently, especially HFC[3] emissions lead to much debate. HFCs are used as one of the alternative refrigerants to CFCs[2] and HCFCs[2] that are being phased out in the Montreal Protocol. However, HFCs are among the gases that are included in the basket of GHGs[4] that is regulated through UNFCCC and Kyoto. The replacement of old (H)CFC containing applications with new HFC containing ones, combined with a general growth of R+AC sectors, leads to an increase in HFC emissions. Global warming is expected to add to the increased demand for refrigeration and air conditioning. This trend is seen as undesirable by policymakers because it might undermine the goal to reduce the total volume of GHG-emissions. Several European countries have therefore introduced policy strategies to mitigate the HFC emissions from the R+AC sectors. Recently, the desire to unify legislation within the EU territory has initiated discussion over which policy strategy should be followed, and led to the introduction of the EU F-gas regulation [European Commission, 2006b] and the MAC-directive [European Commission, 2006a].

Sterman [2002] states: “Understanding complex systems requires mastery of concepts such as feedback, stocks and flows, time delays, and nonlinearity”. In environmental sciences, complex systems are therefore often represented in stock-flow diagrams that visualize the relations between resource flows through the system [Ford, 1999; Meadows, 1972]. Figure 4.1 shows a stock-flow diagram with the flows of HFCs through the R+AC sector. After production the HFC gets filled into cooling applications, where it remains for the lifetime of the application until it gets disposed of. The emissions of HFC to the environment are caused by interplay of two factors: the total stock of HFC in the system and the emission factor[5]. Emission of HFC occurs mainly during use and from applications that are disposed at their End of Life, emission during production is negligable [Palandre et al., 2003].

The literature on policy strategies to reduce emissions broadly focuses on policy feasibility or on emission scenarios. The discussions on policy feasibility mainly focus on whether or not to keep using HFCs. These discussions are often published with limited peer review, outside the scientific arena, or by authors that themselves have a stake [Anderson, 2005; Bivens, 1999; Calm, 2002b; Johnson, 2004a]. They deal either with the technological possibilities to replace HFC refrigerants with alternatives, or with the emission reduction that could be reached by improving containment of HFCs within their application. Policy feasibility literature often overlooks the fact that these measures have

[2] The convention is currently signed by 189 countries. By this convention, signatories are obliged to report to the Conference of the Parties “national inventories of anthropogenic emissions by sources and removals by sinks of all greenhouse gases not controlled by the Montreal Protocol”, annex I countries are obliged to report their emissions inventories annually.

[3] HFC=hydrofluorocarbon, CFC=chlorofluorocarbon, HCFC=hydrochlorofluorocarbon

[4] The gases included in this basket are: CO_2, CH_4, N_2O, PFCs (perfluorocarbons) , HFCs and SF_6.

[5] Emission factor from use is the ratio of HFC emission during operation and maintenance to HFCs in stock. Emission factor from disposal is the ratio of HFC emission at disposal to total amount of HFC at disposal.

different working mechanisms, because replacement aims at the stocks, whereas containment aims at the flows. Related temporal effects are therefore often not regarded in such discussions.

Emission scenario studies, mainly published by or for (inter)governmental bodies [Clodic and Palandre, 2004; IPCC and TEAP, 2005; Schwarz, 2005], do look at temporal effects. These studies estimate future developments leading to certain emission levels of HFCs. However, these studies tend to not critically compare different policy approaches. Typically, instead of comparing the effects of different measures separately, they consecutively add measures to a business as usual scenario to create several emission scenarios with ever increasing effort for reducing emissions. The distinction between measures is thereby lost.

4.2. Research goal

This chapter is inspired by the debate in the EU policy arena and aims to contribute to the discussion on strategies to reduce HFC emissions from R+AC by looking at their different temporal effects. Its goal is to evaluate the differences between strategies aimed at phase out of HFC and strategies aimed at better containment of HFC, caused by the stock-flow system properties. Although based on German data and European policies, it also discusses the implications of these differences in developing countries. Policies that are introduced by 'environmental frontrunner' countries nowadays might be adopted by others later on. Choosing a path now might 'lock in' the pathway for the future. Ultimately, this chapter should contribute to well-informed decision making on future policy developments concerning the R+AC sector, both at EU-level and in general.

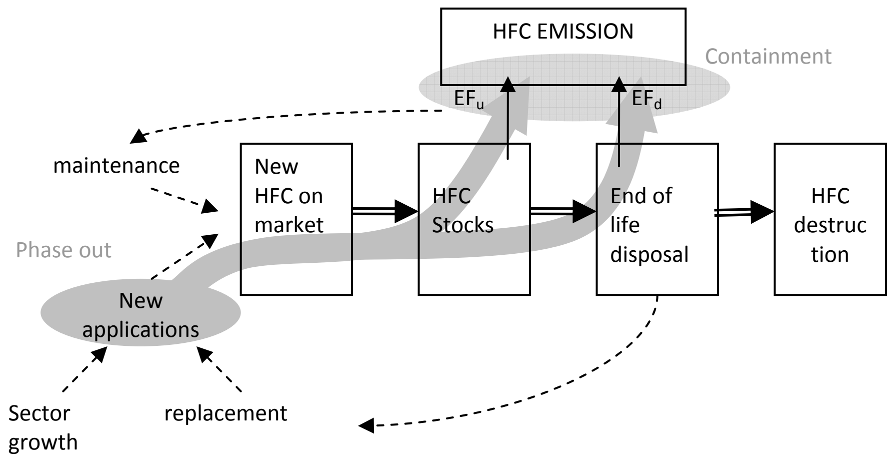

Figure 4.1 Typical stocks and flows of HFC in R+AC sector product system. EF$_u$= Emission Factor from use, EF$_d$= Emission Factor from disposal. Emissions from production are not shown as they are considered negligable. Shaded areas and arrows represent the working mechanism of containment and phase out measures on the system. Double arrows indicate the life cycle of the application, dashed arrows indicate numerical relation.

4.3. System Characteristics

To understand the implications of policy strategies for emission levels, it is important to take a closer look at certain relations between characteristics

of cooling applications at a product level and at a system level. Policy usually targets certain stages of an applications' life cycle; production, installation, use (including maintenance), disposal and destruction. Policy often tries to optimize at this product level. However, at system level, which includes all R+AC applications, but also other societal factors that determine total emissions, such as temporal sector developments and international trade, other considerations might exist. Therefore it is important to understand how changes at product level lead to emissions on the system level. Figure 4.1 shows the relations between emissions and the system life cycle stages.

Several remarks need to be made about this system:

▪ HFC emissions from R+AC are not one time batches, but occur over the entire lifetime of a cooling application. Especially significant are the use and disposal stages [Palandre et al., 2003]. Depending on the annual leakage from usage, the lifetime, and the way of disposal at the end of life of an application, a multitude of the original charge can be emitted over the system's lifetime.

▪ The choice of refrigerant in an application is determined only at the design stage. Once committed to a certain refrigerant, this refrigerant is generally used until the total system is discarded. Retrofitting an application for the use of a different refrigerant often requires system adaptations, is expensive, and can lead to a higher energy use.

▪ Any measure to reduce refrigerant emissions that leads to lower system energy efficiency needs to be regarded with caution. IPCC and TEAP [2005] show that for some R+AC sectors GHG emissions related to energy use are in the same order of magnitude as the emissions of refrigerant, measured in CO_2-equivalent, for other sectors the energy use is an order of magnitude larger. This means that if system energy usage is included in a comparison, the balance of such a measure can very well be negative. Therefore any system adaptation should only be carried out if it results in lower Total Equivalent Warming Impact (TEWI)[6] [Harmelink et al., 2002].

▪ Different refrigerants can have a different theoretical Coefficient of Performance (COP)[7], suggesting different suitability for certain refrigerants [Calm, 2002a]. However, in practice this theoretical difference is often dominated by other factors that influence system efficiency, such as design, maintenance and ambient environment of individual cooling applications. Experts claim that in principle, refrigerant choice is not the principal factor that determines system efficiency[8].

▪ Refrigerants are an essential part of the vapor-compression cooling mechanism. Although a lower charge per system presumably leads to lower annual emissions, physical properties of the system determine an optimal charge. Further minimizing charges is not always an option; it can decrease the system's coefficient of performance and lower the system's cooling capacity [Grace et al., 2005].

[6] TEWI is a cumulative measure for all GHG emissions during a product's life cycle.
[7] COP is a measure for the energy efficiency of an application.
[8] Personal communication Dr. L. Kuijpers

4.4. Policy Strategies

We already mentioned that HFC emission is caused by the interplay of stocks and emission factors. This leads to two policy strategies to reduce emission: reducing stocks, and reducing emission factors. In Europe, both strategies are already implemented in some countries (Table 4.1).

Firstly, Sweden and the Netherlands have similar policy strategies, which aim at reducing emission factors from use and disposal, called "containment" strategies. The Dutch system[9] requires special training of personnel for installation and maintenance, and introduces obligatory leakage controls. The principle behind this strategy is that as long as the HFCs are contained within their application, there is no environmental impact. It aims at existing as well as newly introduced applications. The major risk of such a strategy is that non-compliance to the strict handling procedures is hard to check by inspections. The possible reduction in emission factor is hard to establish, due to very incomplete data [Anderson, 2005; STEK, 2002].

Secondly, Austria and Denmark have introduced legislation that prohibits the use of HFCs in certain applications from a certain date onwards. Similar to the measures to phase out (H)CFCs in the Montreal Protocol, this strategy would lead to a phase out of the use of HFCs. The "phase out strategy" aims at reducing the total stock of products containing HFCs, thereby targeting HFC emissions at the source. Different than the containment strategy, the phase out strategy can in practice only target newly introduced applications; replacing all existing applications would lead to enormous costs to the sector, refilling them with alternatives is not practically feasible due to technical constraints[10]. A phase out of HFC applications is therefore expected to take time, because already existing applications would remain in service until they are disposed of at their End of Life. A risk of this strategy is the availability of replacement options for current HFC applications.

Table 4.1 Pros and Cons of different European policy strategies

Strategy and countries	Pro	Con
HFC Containment Sweden and Netherlands	▪ Targets new and existing applications. ▪ Relatively quick result possible	▪ Requires continuous control stakeholder compliance ▪ Requires education and disposal facilities ▪ Potential risk of release remains
HFC Phase Out Austria and Denmark	▪ No HFC use no HFC emissions ▪ Potential risk of release of stocks disappears	▪ Availability of replacement options questionable ▪ Only new applications
HFC Tax Norway and Denmark	▪ Targets both emissions and stocks	▪ Increases purchase costs of applications

[9] commonly referred to as the 'STEK system'

[10] These arguments are basically the same for this phase-out strategy as they were for introducing the phase-out of (H)CFCs in the Montreal Protocol

Increased TEWI, flammability or toxicity can form barriers for introduction of alternatives [Fischer et al., 1991; Harnisch et al., 2001; Harnisch and Hendriks, 2000; IPCC and TEAP, 2005; Little, 2002; UNEP, 2002].

Thirdly, strategies that aim at both containment and phasing out of HFCs can be found. The Norwegian government has implemented a refund scheme to tax HFC emissions. When buying HFCs or products containing HFCs, a fee has to be paid for their combined global warming potential measured in CO2-equivalents. When the HFCs are offered for destruction, this amount is refunded. This strategy can be expected to on the one hand improve containment since loss of HFC is now very costly, and on the other hand promote the use of lower GWP refrigerants, since the purchase value of products containing HFCs with high GWP will rise. Very recently, the EU has adopted measures that are to be implemented into national legislation of the member countries. A Directive on the use of Fluorinated gases in the Mobile Air Conditioning sector [European Commission, 2006a] prohibits the use of HFCs with a GWP higher than 150 in new car models from 2011 and in all new cars from 2018, this directive thus equals a phase-out strategy. And a regulation on the use of F-gases in cooling applications [European Commission, 2006b] focuses on improving containment of F-gases in cooling applications.

4.5. Methodology

In order to compare the implications of different policy strategies in the short and long term we developed a simple scenario model that simulates the expected emissions from the R+AC sector. The model estimates the emission from each of five sub sectors, leading to a total value for the R+AC sector. The sub sectors considered are: Commercial refrigeration (COM), Industrial refrigeration (IND), Transport refrigeration (TRA), Stationary air conditioning (SAC) and Mobile air conditioning (MAC). We have left out domestic refrigeration, because the low charge and low leakage rate of domestic refrigeration applications make emissions from domestic refrigeration very small compared to other sectors [IPCC and TEAP, 2005]. Moreover, in many European countries, domestic refrigerators do not use F-gases as refrigerant [IPCC and TEAP, 2005].

For each of the sub sectors the annual composition of the following variable quantities are modeled:

- The amount of HFCs filled in new applications
- The total stock of HFCs contained in applications
- The amount of HFCs in applications reaching their End of Life
- The emissions of HFCs from stocks
- The emissions of HFCs from disposal

Emissions from manufacturing are considered to be insignificant in relation to the emissions in the rest of the systems life cycle [Palandre et al., 2003]. Basically, modeling these variable quantities creates a model of stocks and flows of amounts of HFC through the R+AC sector. The relations in this model are visualized in Figure 4.1.

Schaefer et al. [2006] have identified six factors that influence the growth in emissions, four of which have an impact on the growth rate of the sub sectors; replacement of ozone depleting substances, region specific preferences, population growth and income growth. Different assumptions about growth factors or initial stocks can lead to large variation in estimated future emissions (compare e.g. [Schaefer et al., 2006; Schwarz, 2005; USEPA, 2005]). This chapter does not aim to determine future emission levels precisely, but rather aims to show the trends that can occur from following certain policy strategies. Therefore we believe it justified to use a "simplified" projection of future stocks and emissions here, compared to those found in studies that aim to establish future emission levels. Reducing uncertainty about levels of existing stocks and future emissions remains an important issue for further investigation however, as it may demystify the urgency of introducing policy strategy.

In order to be practical, we assume a logistically declining annual growth rate for the size of all the sub sectors, converging to very limited annual growth. Such a growth pattern represents rapid growth for emerging sectors, which declines as the sector becomes saturated. This results in an S-shaped curve, when looking at the development of the sizes of the sectors. From these growth rates we determine how much extra HFC is entering the market each year. After the applications' life time, this amount of HFC will get disposed of. We assume that all applications that reach their end of life will get replaced by new ones. The HFC needed for sector growth plus the HFC in replaced applications form the total demand for new applications in each year.

By establishing an annual emission factor from use (EF_u) we estimate the total annual HFC emissions from use. We also keep track of cumulative emissions to establish the total emission of GHG to the atmosphere over time. Additionally we track the amount of HFC that will get disposed. A disposal emission factor (EF_d) can calculate the expected emissions from disposal. In the model, we assume that all HFC that is emitted during use is refilled each year during maintenance.

The principle of such a stocks-flows system model is valid for any country at any given time. For reasons of clarity, controllability, and data-availability, we chose to base our model on the German situation as an example, and model the period from 1990-2030. This period covers the full period from introduction of HFCs on the market to saturation of the market in Germany.

4.5.1. Model Parameters

Business as Usual scenario

The projection of the five quantities requires the setting of and assumptions on certain model parameters. One of the most determining parameters for future stocks is the expected growth rate of the sub sectors each year. To simulate the expected growth, we have fitted a logistic growth curve to the historic German data on each of the R+AC sectors presented in the German annual inventory report for the UNFCCC [UBA, 2006]. We have assumed a final growth rate of 1% to allow for some growth of the sector due to economic growth. The exact value of this growth is not very important to this research, since we are looking at trends rather than exact data. Our conclusions about the different policy strategies are similar when we assume slightly higher or lower growth rates[11]. We compared the emissions calculated by the model to projections for the German ministry of environment by Schwarz [2005] for 2010 and 2020 and found these to be similar.

[11] Obviously, absolute emission levels vary when using different growth rates.

Average lifetimes of applications (see Table 4.2) are estimated from IPCC and TEAP [2005] and Schwarz [2005]. Base leakage rates during use (EF_u) are calculated for 1990-2004 from the German annual inventory report for the UNFCCC [UBA, 2006]. From the trend visible in these calculations we estimated values for 2030 and interpolated in between. Notice that the average emission factor in Germany (9.4% in 2002 [UBA, 2006]) is much lower than the world average (18.6% in 2002 [UNEP, 2005]). Disposal emission factors are (EF_d) assumed to be 50% for all sectors except MAC based on UNEP [2005]. For MAC we

Table 4.2 Values for certain model parameters in BaU and other scenarios

Sub sector	EF_u (%) 2004/2030	Life time (yr)
TRA	12.7 / 12	12
IND	7 / 7	15
COM	9.6 / 8.6	9
SAC	5.0 / 4.5	15
MAC	10.4 / 10	12

Table 4.3 Values used for the figures and tables presented in the results section

Scenario	Year of implementation		Reduction EF_u (red) or HFC phased out (po)		Speed of implementation	
	General	MAC	General	MAC	General	MAC
Containment (Figure 4.4, Table 4.4)						
2000 quick	2000		40%red		Quick	
2000 slow	2000		40%red		Slow	
2010 quick	2010		40%red		Quick	
2010 slow	2010		40%red		Slow	
Phase Out (Figure 4.5+Figure 4.6, +Table 4.6)						
2000 quick	2000		50%po	100%po	Quick	
2000 slow	2000		50%po	100%po	Slow	
2010 quick	2010		50%po	100%po	Quick	
2010 slow	2010		50%po	100%po	Slow	
Comparisons (Figure 4.7+Figure 4.8)						
Containment	2008		40%red		Quick	
Phase out slow	2008		33%po	33%po	Slow	
Phase out quick	2008		50%po	100%po	Quick	
EU directives	2008	2011	30%red	100%po	Inter-mediate	Slow
EU phase out	2008	2011	50%po	100%po	Slow	Slow

have assumed 100% emission as base. UNEP [2005] assumes best practice of 50% for MAC in Europe, but 0% in the rest of the world. These assumptions together form our business as usual scenario which forms the basis of possible policy strategy scenarios.

Policy strategies scenarios

To simulate the introduction of policy strategies, the model parameters are changed from a desired year of implementation onwards, to create several sets of scenarios. “Containment” scenarios are represented by assuming Emission Factors from use will decrease. “Phase out” scenarios are represented by reducing the percentage of HFCs in new applications. Notice that “phase out” can be reached by banning use of HFCs in certain applications as well as by lowering charges of HFC. To represent adaptation time required by the sectors, an implementation speed is set to immediate (0 years), quick (2 years), intermediate (5 years) or slow (10 years). In this transitory period the policy’s effect gradually increases from no to full effect. Table 4.3 shows the values used for the figures presented in the results section.

4.6. Results

In this section the most illustrative results of several modeling exercises are presented and some of the teachings are discussed. The section is divided into four sub sections; it describes firstly the results of the BaU scenario, Containment scenarios and Phase out scenarios and concludes with a comparison of containment and phase out scenarios. As explained, the values presented here are representative for Germany, but should be interpreted in a general way.

4.6.1. “Business as Usual” scenario

The Business as Usual (BaU) scenario represents the development of the five different R+AC sectors in case no additional policy is introduced. As expected, the model shows us that in this scenario, the stocks of HFC increase rapidly in the beginning and level off later, when the market becomes saturated (Figure 4.2). We see that the MAC and COM sector together represent 70% of the stocks in 2030.

The total yearly emission of HFCs follows the trend seen in the stocks (Figure 4.3). Because of their relatively high emission factor compared to other subsectors, the MAC and COM sector’s share of total emissions from use in 2030 (78%) is even larger than their share in stocks. Two important conclusions can be drawn from this scenario. Firstly this scenario shows us the important contribution of MAC and COM to the total HFC emissions. Emissions from MAC form 43% of the total emissions from use, COM adds 34%. It is obvious that efforts to reduce emissions should mainly aim at these two sectors. Secondly, the BaU scenario shows us the increasing importance of disposal emissions. Notice that the amount of HFCs in discarded applications currently is relatively low, but rises to about equal the yearly emissions from use. Dependent on how the disposal of these applications is treated, this might be an important source of additional emissions. This means that preventing End of Life emissions will become equally important as preventing emissions during use. In the BaU scenario this additional emission from disposal rises to 62% of the emissions from use.

4.6.2. *"Containment" scenario*

Figure 4.4 shows the total annual HFC emissions from R+AC when introducing measures that reduce the percentage of emissions from use with 40%. The different plots show the effect of introducing these measures in 2000 and in 2010, and with two different introduction speeds. The "containment strategy" leads to overall lower emissions than in the BaU scenario. This emission reduction is notable directly from the year of

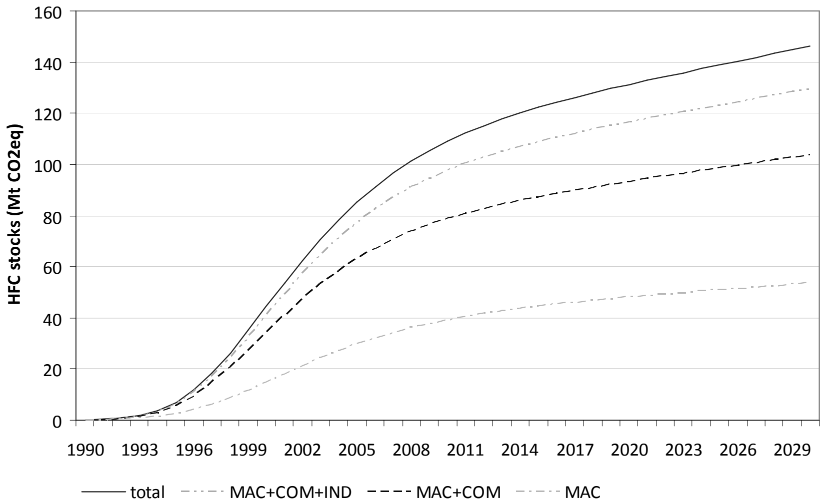

Figure 4.2 Development of the Stocks of HFCs over time in the BaU scenario.

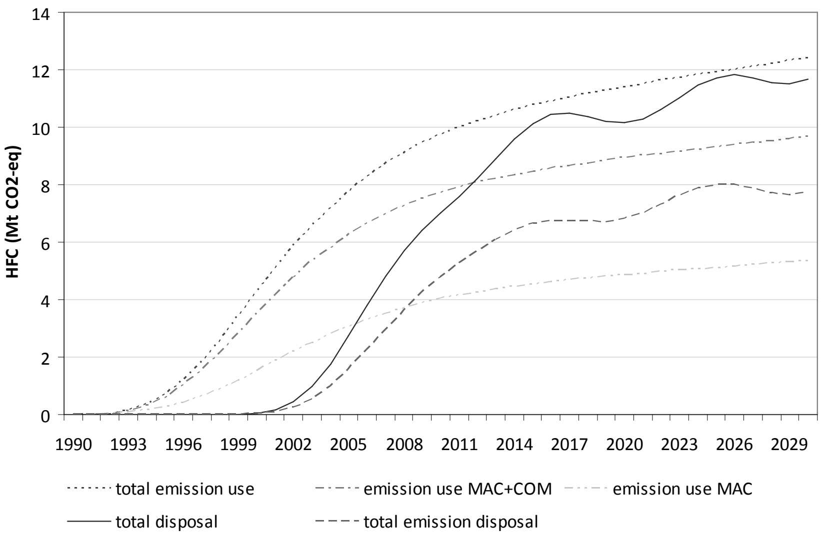

Figure 4.3 Annual emissions of HFC from use and from disposal and annual amount of HFC in applications that reaches the disposal phase (BaU scenario). The "ripples" result from model imperfections.

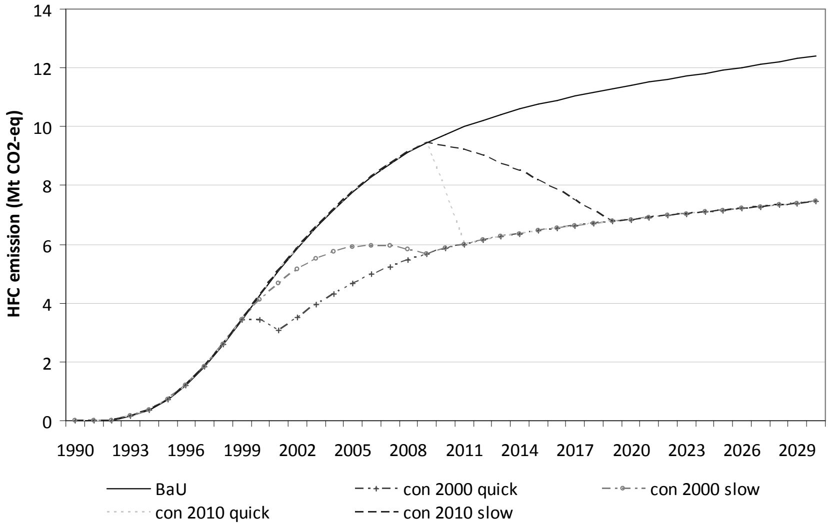

Figure 4.4 Annual HFC emissions from use in BaU scenario and in scenarios with measures that reduce the emission factor from use by 40% (containment scenarios). The graph shows the difference between starting measures in 2000 or in 2010 and between a quick or slow implementation of the measures. The arrow indicates that the line representing the emission shifts upwards when a lower policy effect is assumed, and shift downwards when a higher effectiveness is assumed.

Table 4.4 Cumulative emissions from use in BaU and containment scenarios, and relative emission reduction in containment scenarios compared to the BaU scenario

	Cumulative emission containment 1990-2030	Emission reduction compared to BaU	
	(Mt CO2-eq)	(Mt CO2-eq)	(%)
BaU	320	0	0%
2000 quick	197	123	38%
2000 slow	207	103	35%
2010 quick	227	93	29%
2010 slow	243	77	24%

implementation onwards[12]. Notice that apart from the emission reduction from policy introduction, emissions follow the increasing trend of the stocks. The consequence of this is that for countries that implement measures relatively late in the development of the sectors, annual emissions can be reduced for a prolonged period of time, however countries that are still relatively early in their development of the sectors, will see their annual emissions rising even when introducing containment measures. Final emissions depend on how much reduction in emission factor is possible. Notable is that the final

[12] We have assumed that containment options are generally applicable to both existing and new stock. Introduction of some containment options may however be feasible in new stock only, due to technical or cost related restraints. In such cases, containment options could “phase in” comparable to “phase out” options.

emission level is independent of the year of implementation. The cumulative emissions from use are represented by the area under the plots. The difference between areas of different scenarios reflects the additional, or reduced, emission by e.g. implementing policies later or earlier.

End of Life disposal

Table 4.4 gives an indication of the relative significance of the difference between early or late and slow and quick implementation. In our scenarios, implementing measures 10 years early leads to 9-11% extra cumulative emission reduction, faster implementation can lead to 3-5% extra reduction.

In the containment scenarios, the build up of stocks in the sub sectors remains the same as in the BaU scenario (see Figure 4.2). This means that the emissions from End of Life disposal play an equally important role. Measures that lead to reduced emission from

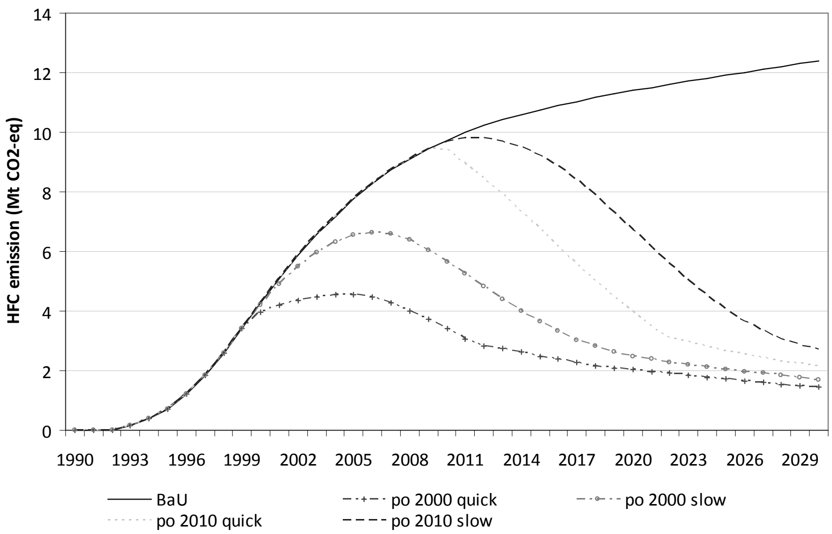

Figure 4.5 Annual HFC emissions from use in BaU scenario and in scenarios with measures that lead to total phase out of HFC use in new MAC applications and 50% phase out of HFC use in other applications. The graph shows the difference between starting measures in 2000 or in 2010 and between a quick or slow implementation of the measures.

Table 4.5 Cumulative emissions from use in BaU and phase out scenarios, and relative emission reduction in phase out scenarios compared to the BaU scenario

	Cumulative emission Phase out 1990-2030 (Mt CO2-eq)	Emission reduction compared to BaU (Mt CO2-eq)	(%)
BaU	320	0	0%
2000 quick	98	222	69%
2000 slow	132	188	59%
2010 quick	183	137	43%
2010 slow	220	100	31%

disposal can be simulated in the same way, and will show similar effects on the emissions from disposal as the effects that containment measures have on emissions from use, therefore we will not further elaborate on this.

4.6.3. "Phase out" scenario

Figure 4.5 shows the total annual HFC emissions from use in R+AC sectors when introducing measures that lead to phase out of HFC use in applications. This figure shows that if a phase out measure is implemented sooner or quicker, the emission levels will remain lower. This is because the sooner or quicker a phase out is implemented, the less stocks of HFCs in applications will be built up. However, if the implementation strength of measures is too low (e.g. only 25% of HFCs in new applications is phased out), early implementation is less effective, because the increase in HFCs due to the initial rapid market growth will then lead to a build up of stocks anyway. Figure 4.5 also shows that in most scenarios, the level of emission decreases some years after the introduction of these measures. The delay occurs because phase out measures target only the HFCs in new applications. Emission levels of HFCs that were already in old applications remain the same until these applications reach their End of Life. The more HFCs get phased out, the more emissions from use will decrease. Because we assume that a certain share of all applications that contain HFCs that reach End of Life gets phased out, the total phased out share increases over multiple lifetimes. Due to this mechanism, emissions will decrease significantly even at low implementation strengths. A third observation from Figure 4.5 is that emission levels have a wide variation between different scenarios. The relative significance of this distinction in cumulative emissions is shown in Table 4.5.

An important observation in the phase out scenarios is that because less HFCs are placed on the market in applications, the amount of HFCs that reaches End of Life decreases (Figure 4.6 and Table 4.6). This obviously has important consequences for the emissions from disposal. If less HFCs reach the disposal stage, less will be emitted. The difference between areas under the curve of different scenarios reflects the additional, or reduced, total amount of HFC at disposal by implementing policies later or earlier (or slower or faster). Especially the difference between early and late implementation is striking.

4.6.4. Comparison of containment, phase out, and mixed strategies

The exact level of emissions in each scenario depends strongly on the assumptions about the timing, speed and strength of implementation of the respective strategies. Extreme assumptions such as very large reduction of emission factors, or immediate phase out of all HFC use in all new applications can make every strategy look very appealing for mitigating HFC emissions. It is not our intention to discuss the exact numbers that are feasible, but rather the general trends visible when taking mediocre numbers.

We have already noted that containment strategies lead to emission reduction directly, whereas phase out strategies take some time to be effective. Because the total amount of phased out HFC increases over multiple lifetimes, in the long run phase out strategies generally show a lower annual emission. Obviously, at some point in time in between, containment and phase out strategies will break even. A break even point exists both for annual emissions, and for cumulative emissions. Cumulative emissions are important to look at, because GHGs remain in the atmosphere for a prolonged period of time, thus leading to increased radiative forcing during a longer period. However, in international treaties such as the Kyoto protocol, the annual emissions also play a large role.

Figure 4.7 and Figure 4.8 give examples of several phase out and containment strategies. If we assume all new MAC applications and one in every two other new applications could be HFC free in five years from 2008 onwards ("phase out quick"), annual emissions from use would break even with the emissions from a scenario with quick realization of 40% emission reduction by containment ("containment") in 2015, and cumulative emissions from use would break even in 2023. The benefits of a phase out strategy will start slightly earlier, if emissions from disposal are taken into account. We can see that a scenario which assumes lower implementation strength of phase out measures ("phase out slow": one in three new applications will be HFC free in ten years from 2008 onwards), the break even points are much farther away.

A roughly outlined simulation of the recently adopted EU legislation [European Commission, 2006a; , 2006b] ("EU directives": 100% phase out of HFC use in MAC in ten

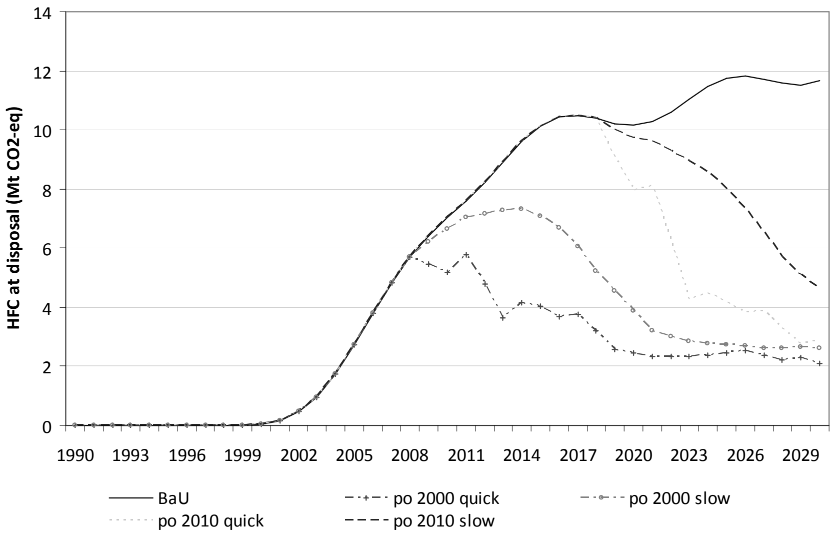

Figure 4.6 Amount of HFCs in applications that reach their End of Life in the same scenarios as in Figure 4.5 (phase out).

Table 4.6 Cumulative amount of HFC that reaches End of Life stage in the period 1990-2030 in BaU and phase out scenarios, and relative reduction in phase out scenarios compared to the BaU scenario

	Cumulative amount of HFC at EoL 1990-2030 (Mt CO2-eq)	Emission reduction compared to BaU (Mt CO2-eq)	(%)
BaU	243	0	0
2000 quick	93	150	62
2000 slow	123	120	49
2010 quick	171	72	30
2010 slow	203	40	16

years from 2011 onwards and a 30% emission reduction in the other sub sectors in five years from 2008 onwards) shows the effects of a mixed strategy. The phase out of HFCs in MAC, which is the largest contributor to emissions and stocks, from 2011 onwards leads to a marked decrease of annual emission in the long run. However since emissions from MAC remain unabated in the period until total phase out, total emission levels from use will remain almost stable rather than drop until 2017, even though emissions from the other sector will be reduced. Moreover, when the MAC phase out is completed, the emissions from the other sub sectors will remain. Generally, this mixed scenario scores better than phase out scenarios in the short run, and scores better than containment scenarios in the long run. To articulate the differences with a phase out scenario in the

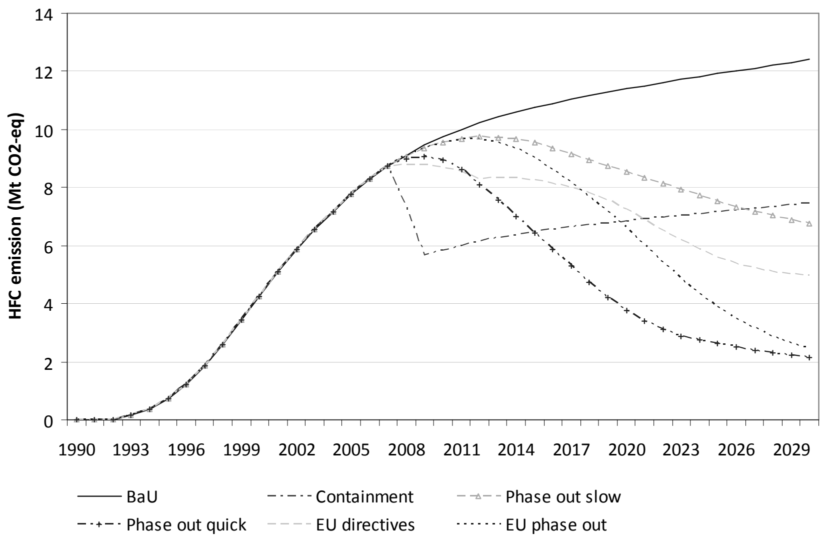

Figure 4.7 Annual HFC emission from use in several different emission scenarios

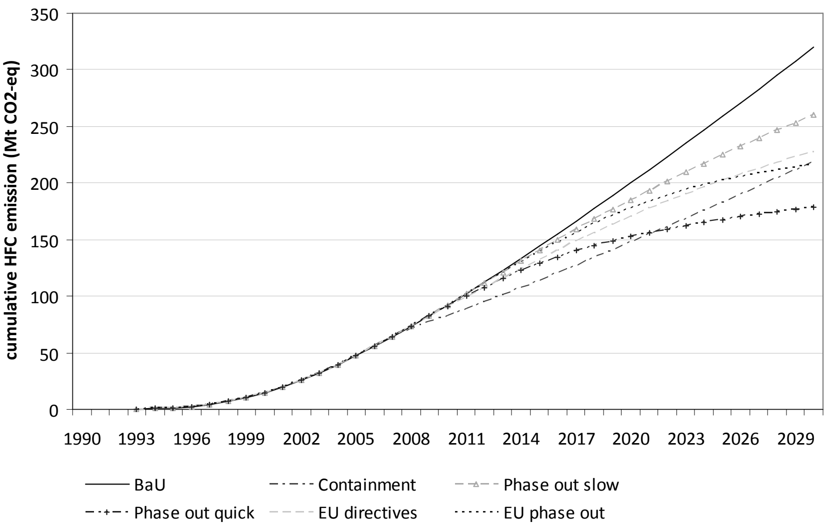

Figure 4.8 Cumulative HFC emission from use in several different emission scenarios

same spirit, the “EU phase out” scenario was drawn up (MAC phase out similar, phase out of half of the HFCs in new applications in 10 years from 2008 onwards instead of containment). This comparison shows annual emissions break even in 2018, and cumulative emissions favor “EU phase out” from 2025 onwards.

4.7. Discussion

4.7.1. Discussion of results

Our model suggests that because of the stock-flow dynamics of the R+AC system, the choice between containment and phase out strategies is, in fact a choice between minimizing short term or long term HFC emissions. For mitigating climate change, looking at emissions over a long term is the most relevant, because climate change is a long term problem, with GHGs often remaining in the atmosphere many years after emission. This suggests a preference of phase out strategies over containment strategies; a phase out of HFCs presumably finally leads to lower emissions than could be reached by optimal containment, provided that either strategy does not lead to energy efficiency changes. However, this does not mean that containment strategies could not lead to politically acceptable levels of emissions. Moreover, several barriers exist that might lead to preference of containment strategies instead.

The first barrier is a possible preference of policy makers for short term results. Setting short term targets enables early control in case such targets are not achieved. On the other hand such targets might lead to non-optimal solutions; e.g. to benefit the Kyoto targets, which cover the period 2008-2012, a containment strategy is more effective than a phase out strategy. Looking past Kyoto reverses this picture.

A second barrier involves the temporal distribution of the costs involved in the different strategies. In a containment strategy, stakeholders are obliged to take measures that reduce emissions. These measures include training personnel, keeping logs and periodical checking for leakages or installing leakage detection systems. Moreover destruction or reclamation facilities are needed to dispose of or reclaim recovered HFCs and control agencies are needed to check compliance. These measures, institutions and facilities remain necessary, and will keep imposing costs, as long as stocks of HFC exist. A phase out strategy initially requires investments in technology to design alternative cooling systems that perform equally well, but do not use HFCs. Development and introduction of such new technology is usually relatively costly. However, when such technology can be introduced, no additional training, institutions or facilities to prevent HFC emissions are required[13]. This final situation seems in favor of a phase out strategy. However, temporal discounting in economics devalues costs that are further away in time, which benefits containment strategies.

These two barriers might lead to a lock-in situation, which itself could form a third barrier. When initial focus lies on containment, emissions will be lower than before, thus there is less urgency to change. Secondly, after the phase out of CFCs due to the Montreal protocol, and then the introduction of containment measures, changing for a third time in a short time span is bound to frustrate stakeholders.

[13] Depending on technology, alternatives might require special handling as well, due to toxicity or inflammability.

Therefore if the ultimate goal would be a phase out, it seems wise to start this phase out as soon as possible. The decision on whether or not total phase out is required depends on the emission level that is acceptable. This is, amongst others, a matter of political choices.

The mixed “EU directives” scenario shows results that are in between the results for phase out or containment scenarios. The immediate effects reached by containment in most sub sectors lead to lower emissions in the short term, which might be attractive to policy makers that aim for quick results. The phase out in MAC leads to decreasing overall emissions in the long term, which can help to reach climate goals. Thus, if the recently adopted EU legislation follows this course, it can be expected to break the trend of increasing emissions. The “EU phase out” scenario shows that slowly phasing out HFC use in all sectors will ultimately lead to even lower emissions.

Obviously, if measures are combined, the results will be stronger than either containment or phase out separately. The Norwegian refund scheme is expected to affect both purchase and handling of applications containing and might therefore show characteristics of such a combination.

The effects on emissions strongly depend on the effectiveness of policies. Robust data on policy effectiveness is currently lacking. It would therefore be interesting to compare the effects of different policies currently in effect.

Our results also show that the timing of measures can have a large impact on the cumulative emissions from the R+AC sector. This is especially striking in the case of phase out strategies. Earlier and faster implementation of a phase out strategy decreases the cumulative emissions markedly. This is very important for developing countries, which have not yet built up a large stock of HFCs. Limiting or preventing stock build up by immediately introducing alternatives can prevent much emission, and thus prevent having to introduce control measures in the future.

4.7.2. Discussion of method

We chose to base our simulation on the situation in Germany as a general example for a typical European country. Germany had not set special legislation on F-gases prior to the recent EU regulations, thus we assume that developments here can be taken as generally extrapolatable to other countries that have also set no regulations. Furthermore, data on the historic development of the different R+AC sectors are available from the German government [UBA, 2006]. Also, the German government has performed and ordered many research projects in anticipation of future F-gas policies [Schwarz, 2005; UBA, 2004]. Thus data on the German situation are readily available.

The model is based on historic data from 1990 to 2004 [UBA, 2006] and estimates emissions and stocks onwards to 2030. The period 1990-now is not directly relevant for comparing possible policy strategies in Germany, since such strategies can of course not be implemented retrospectively. However, this period becomes relevant when we discuss developments in developing countries. Historic trends for Germany can serve as future estimates for developing countries. By including this period we can investigate the implications of implementing policies earlier in developing countries than they are implemented in Germany.

The period to 2030 is chosen to be able to highlight better the temporal effects of policy strategies. With policies implemented over the coming years, and life-times of applications of about 10 to 20 years, full effects of policies for new applications will be visible only after considerable time.

The way we designed the model, makes the stocks in the BaU scenario automatically equal the potential market sizes for the other scenarios. This means that the share of the markets that is currently already using alternatives to HFCs as refrigerant is neglected.

To test the robustness of these assumptions we have determined the effects of changing these assumptions on our final conclusions.

4.8. Conclusion

The growing demand for cooling applications throughout the world, possibly increased by global climate change, requires the implementation of policy strategies to mitigate the related increase in GHG emissions from energy and refrigerant use in the R+AC sector. This chapter discusses the effects of the stock-flow dynamics on HFC emissions from the R+AC sector. Simulating emissions from this system in different scenarios, leads to the following conclusions.

Stock-flow dynamics have an important influence on the development of HFC emissions from the R+AC sector. Policy strategies that directly target emissions, called containment strategies, can reduce emissions significantly in short time. Policy strategies that target the stocks of HFC in applications, called phase out strategies, take some time to become effective. In the long run they often lead to lower emissions than containment strategies. In terms of annual GHG emission, the choice between containment and phase out strategies is therefore in fact a choice between minimizing short term or long term emissions.

Although maximizing long term effects is most beneficial in mitigating climate change, time preference in politics and economics might create barriers that could lead to short term optimization instead, possibly leading to a lock in situation.

If unabated, emissions from disposal can lead to equally large emissions annually as those from use. These emissions are currently not occurring yet, because most HFC equipment has not yet reached its end of life. In a phase out strategy, the stocks of HFC in application are phased out, or do not build up at all.

Early and quick implementation of phase out strategies could lead to important reductions in cumulative HFC emissions, because stock build up is prevented. This timing effect is less pronounced for containment strategies. This suggests policymakers should prevent delay in effectuating policy strategies. This is also a very important conclusion for developing countries, when we assume similar development of HFC use in developing countries as that in Germany. Limiting or preventing stock build up in developing countries by immediately introducing alternatives for HFCs, while maintaining or improving energy efficiency, can prevent much HFC emission, and thus prevent having to introduce control measures in the future.

Large uncertainties remain about current and future stock and emission levels globally. The extent to which the different policy strategies can be implemented successfully depends on both technological and other factors. Future research should resolve these uncertainties to be able to compare different policy strategies on an absolute basis.

5. REFRIGERANT EMISSIONS FROM A GLOBAL GOVERNANCE PERSPECTIVE[1]

Abstract *The growing global demand for refrigeration and air conditioning (R+AC) systems is expected to lead to increasing emission of high GWP refrigerants. Preventing climate change requires a globally effective policy approach to mitigate these emissions. This chapter analyzes the policy approaches to effectuate global emission reduction from R+AC systems, which are categorized in containment strategies and technology shift strategies. The chapter takes a long term perspective which implicitly requires policy effectiveness in both industrialized and developing countries.*

The chapter investigates the strategies by integrating a physical, a socio-economical and a policy system perspective. Each of these systems sets preconditions for effective policy effectuation. The integration of these systems establishes a global governance system framework, which is used to assess seven currently existing or considered policy approaches to control refrigerant emissions from R+AC systems.

The chapter concludes that containment strategies are not likely to form effective long term solutions, because physical restraints limit their reduction potential and institutional restraints limit their effectuation in developing countries. Moreover it concludes that strategies aimed at technology shifts may be more positive, by inducing global stakeholders to develop the required technologies and enabling technology leap-frogging, especially if the financial burden is carried by industrialized countries.

5.1. Introduction

For ages, humans have improved their living conditions by developing ever more comfortable ways to fulfill their basic or advanced needs. Such developments have made human society ever less dependent on the irregularities of its natural surroundings. The development of refrigeration and air conditioning (R+AC) systems and their facilitation of secure food storage, industrial processes and improvement of our physical living conditions are prime current day examples of mankind's desire to continuously improve comfort by manipulating our surroundings.

[1] This chapter is a slightly adapted version of Hekkenberg, Moll and Schoot Uiterkamp (submitted). *Refrigerant emissions from a global governance perspective.*

The continuous demand for better living and working conditions is not the only driver for the observed increasing use of R+AC systems globally [ACHRN, 1999]. Other drivers add to this development. For example, a growing world population increases the demand for food and therefore requires better food preservation to avoid spoilage losses; globalization and the institutional arrangement of modern societies require a secure and safe food supply chain in which food can be preserved over longer time periods and recently, increased global surface temperatures add to the demand for R+AC. The continuation of these developments, expectedly leads to a massive further increase of the use of R+AC systems throughout the world [IPCC and TEAP, 2005]. This increase may be especially notable in developing countries, with high population and generally warm climates.

Many socio-economic activities imply active intervention in the physical environment. Resource depletion, land use change and harmful emissions interact with the natural systems that support human (and other) life. The continuous expansion of the socio-economic system leads to increasing environmental pressure. In parallel with the expansion of our socio-economic system, the scale of its environmental impact has expanded from local to global.

Refrigeration and air conditioning show how the very developments that aim to improve our individual living comfort locally may simultaneously threaten it collectively on a broader scale. Refrigeration and air conditioning systems aim to stabilize local temperature conditions, however, emissions of greenhouse gases (GHGs) and ozone depleting substances (ODSs) related to their (energy and) refrigerant use contribute to global climate change [Fischer et al., 1991] and the depletion of the stratospheric ozone layer. The use and emissions of fluorinated refrigerants with high global warming potentials (GWP) are especially notable in this regard [IPCC and TEAP, 2005]. Through the Montreal Protocol [UN, 1987], ozone depleting *and* high GWP chlorofluorocarbon (CFC) refrigerants are being replaced by hydrofluorocarbon (HFC) refrigerants that 'only' have a high GWP[2]. The expected increasing use of R+AC systems globally is expected to lead to correspondingly increasing emissions of HFC refrigerants [IPCC and TEAP, 2005], leading to increasing pressure on the global climate.

Global climate change is one of the current main concerns of the expanding socio-economic system. A drastic cut in global GHG emissions is necessary in the next decades to prevent possible catastrophic climate change [IPCC, 2007]. National and international climate policies therefore aim to manage the rate of GHG emissions from our socio-economic system. Because of their expected growth, successful governance of refrigerant emissions is an essential part of climate policies aimed at reducing global GHG emissions.

Primarily, possible strategies to reduce refrigerant emissions depend on the physical characteristics of processes involved in producing and operating R+AC systems and the characteristics of stakeholders in these processes. However, as will be discussed in this

[2] GWPs of different HFCs vary considerably. E.g. the recently developed HFC-1234yf has a very small GWP (4) [DuPont, 2008] compared to the GWP of HFC-23 (14800) [IPCC, 2007]. Moreover, other (natural) refrigerants exist that generally have low GWPs. This chapter focuses on the emissions of high GWP HFC refrigerants. Therefore, in this chapter the terms *refrigerants, HFC-refrigerants, or high-GWP refrigerants* refer to high-GWP-HFC refrigerants exclusively, unless otherwise specified.

chapter, the effect of policies also depends on the existing institutional conditions that enable reduction strategies.

Historically, emissions of fluorinated refrigerants originate mainly from industrialized countries. In accordance with the principle of 'common but differentiated responsibilities' [UN, 1992a], industrialized countries are currently taking the lead in effectuating climate policy. Current policies to reduce refrigerant emissions are therefore based on the institutional conditions in industrialized countries. Several policies exist, each of which may be expected to be successful within its jurisdictional borders.

However, a successful global climate policy also requires governance of emissions in developing countries, in which institutional conditions are often lacking or not adequate. Understanding how institutional conditions interact with possible policy strategies in developing countries is needed in order to assess the possibility to expand current policies to developing countries. In order to prevent lock-in into polluting technologies, policies in industrialized countries should preferably enable developing countries to 'leap-frog' polluting developments and follow a non-polluting or less polluting development pathway as soon as possible.

For reasons of cost-effectiveness, the stakeholders operating in the global market for R+AC systems generally prefer uniform policy strategies rather than locally differentiated ones [EPEE, 2005]. Therefore, investigating which type of policy can be successful on a global scale is needed to facilitate global refrigerant emission control.

5.2. Aim

This chapter investigates whether (and which) currently existing policies to reduce the climate impact from high-GWP refrigerant emissions can be successfully introduced in developing countries. In order to do this, it first investigates the "*physical system*" which consists of the relevant physical relations between functional processes in the socio-economic system that are involved in producing and consuming R+AC systems.

Next, it assesses the socio-economic playing field in which this physical product system is embedded. The resulting system of interacting stakeholders operating the various physical processes is called the '*governance system*', which forms the base for policy intervention.

Next, the study analyzes how the interaction of the physical and governance systems leads to two principal policy strategies to reduce refrigerant emissions: *containment* or *technology shift*. Then, it investigates how the different principal policy instruments, *financial* or *command and control*, can result in either strategy. This generates a 2x2 framework of instrument-strategy combinations that can be used to categorize existing refrigerant emission reduction policies. Lastly, it discusses how differences in institutional conditions in developing countries can influence the effectiveness of each of the instrument-strategy combinations in the policy framework.

5.3. The 'physical system' underlying emissions

From a physical perspective, GHG emissions originate from a multitude of physical processes that are systematically linked (the "*physical system*") to provide a multitude of societal functions and widely varying utility by and for a multitude of different stakeholders. Although intricately linked, the processes in a physical system producing one type of product or service can be traced back and ordered directionally in time, as if to reconstruct the origin of a single 'average' product. Physical systems are used in approaches such as life cycle assessment (LCA) [Guineé, 2002] to assess the environmental impacts associated with consuming one particular product or a set of products in a consumption pattern. Such a comprehensive physical assessment enables a special policy focus on the activities that contribute most to the environmental impact of interest. However, these physical assessments generally only generate direct relations between processes and impacts. Still, depending on the process, emission impact from a given life cycle process may result (partly) indirectly from 'upstream' processes.

As noted in the introduction, refrigeration and air conditioning systems contribute to climate change mainly by their energy and refrigerant use [Fischer, 1993]. Refrigerant emission originates most notably from the processes of system operation, system maintenance and system disposal [Hekkenberg and Schoot Uiterkamp, 2007]. However, refrigerant emission during operation of R+AC systems can be controlled only partly by their system operators. Effectuating a responsible maintenance and disposal regime can limit the amount refrigerant leaking out of the system. However, system operators are bound to physical system specifications (at least temporally until the system can be economically depreciated), including the type and amount of refrigerant used and leak tightness (which are determined during system manufacturing) and to the available waste disposal systems. Such dependence may be particularly relevant in the case of system operators in developing countries who can only afford economically depreciated systems (illegally) exported from industrialized countries.

R+AC system specifications are in turn restrained by available cooling technologies and available refrigerants, the physico-chemical properties of which determine their global warming potential (GWP). GWPs of available refrigerants vary from zero to several thousands [IPCC and TEAP, 2005]. Emission impact is thus highly dependent on the type of refrigerant. Arguments such as toxicity, flammability and (consequently) high investment costs related to designing refrigeration systems based on low GWP refrigerants or different technologies lead to the common use of high GWP refrigerants in R+AC systems [UNEP, 2002].

Thus, system design in upstream processes contributes to the climate impact of emissions in downstream processes. Therefore R+AC system emissions can be accounted towards both upstream and downstream processes in the physical system.

Figure 5.1 shows the relations in the physical system that are most important to life cycle emissions of R+AC systems. Understanding the physical interactions between processes is important in order to be able to reduce emissions from (the most significant) processes. Note that the importance of various relations may differ in different types of R+AC systems; e.g. some systems hardly require any servicing, and most AC systems do not contain foams.

The physical system properties define two main strategies to reduce the climate impact from refrigerant emissions; improved *containment* of the refrigerant in the physical system (by integrated chain management) including reducing charge volumes

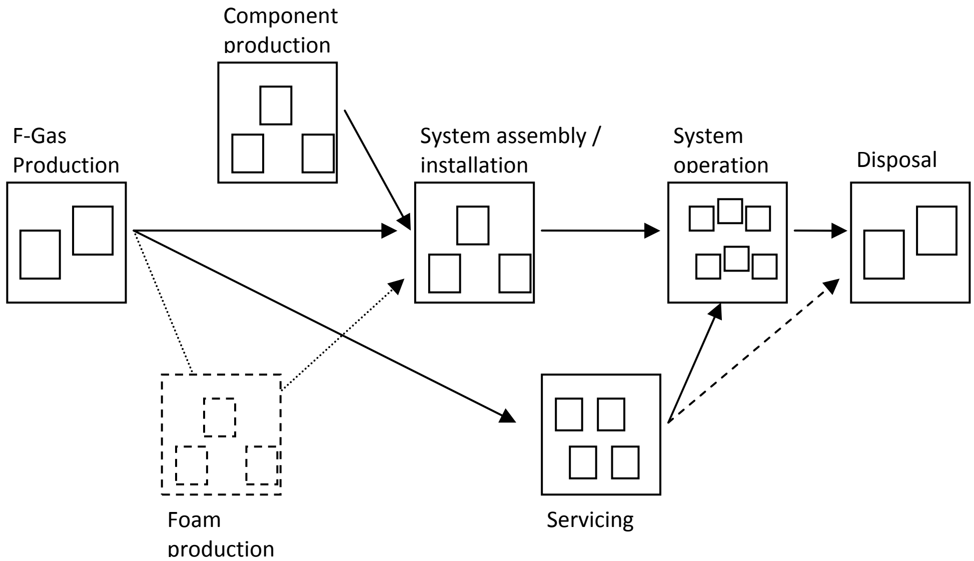

Figure 5.1 Schematic representation of the activities in the physical system for refrigeration and air conditioning systems In such physical approach, processes are grouped by similar functions (activities). Note that foam production is generally irrelevant for AC equipment and not all systems require servicing.

or *technology shift* towards using different (low-GWP) refrigerants or cooling technologies [Hekkenberg and Schoot Uiterkamp, 2007]. The feasibility and effectiveness of these two emission control strategies depend on the governance system in which the physical system is embedded, as will be discussed in sections 5.5 and 5.6. First, section 5.4 will introduce the concept of the governance system.

5.4. The 'governance system' underlying emission policy

Policies can not simply change the processes in the physical product system themselves, but have to act through (and are influenced by) the stakeholders that operate these processes [Bressers, 2004; Bressers and O'Toole, 1998]. From a socio-economic perspective, the physical system can be regarded as a interweaved network linking stakeholders that provide goods or services (producers) to other stakeholders (consumers), who may or may not themselves be providing yet other stakeholders. Each process is operated by an individual stakeholder, who operates in a context defined by physical, socio-economic and institutional relations, that already exists before the implementation of any emission control policy [Bressers, 2004]. Controlling emissions from the physical product system therefore implies successfully altering the context in which individual stakeholders operate.

Comparable to the physical system, we thus define a '*governance system*', which covers the multitude of stakeholders in the socio-economic system involved in producing all similar products or services. Such a governance system does not only include the formal relations with other stakeholders, but also includes the (institutional, socio-economic) context in which the stakeholders operate. The governance system therefore comprises several dimensions that may each have variable characteristics. Three of these dimensions are important in our assessment.

Firstly, similar processes occur at various places throughout the world and at various points in time. Territorial, social and jurisdictional differences may therefore create different operating contexts for otherwise comparable stakeholders. The institutional capacity and political priorities of different governments may affect the opportunity for different types of policy intervention [Dolowitz and Marsh, 1996; Tews, 2005; Willems and Baumert, 2003].

Secondly, different activities in the physical product system are subject to different economic realities. Production of refrigerants and 'plug-in' systems occurs in a globally competitive market, whereas installation, service and use are generally local processes. This difference in market orientation between upstream and downstream stakeholders is likely to influence the opportunities for possible governance strategies [Schreuder, 2009a].

Lastly, the number and type of stakeholders involved in each activity of the physical product system differ between the producer end (upstream) to the consumer end (downstream). Generally upstream stakeholders are few, whereas downstream stakeholders are many, even though the system may theoretically sometimes converge in some activities. The number and type of stakeholders involved in an activity can also influence the opportunities for different types of governance. E.g. it may be related to available power resources (exclusive information [Pettigrew, 1972], economic power) which can be used to obstruct given policies, to the capacity of stakeholders to comply to regulation and to the possibility to verify compliance by stakeholders [Willems and Baumert, 2003].

Figure 5.2 shows these three dimensions in a schematic representation. The variation in these dimensions of the governance system may result in differentiated opportunities for policy intervention in different processes and in different countries throughout the world. The governance system can therefore be interpreted less straightforwardly than the physical system. However, understanding the variation in the governance system is indispensible for an assessment of different policy options in developing countries.

Assessment at the governance system level allows linking the conditions set by the physical system with the conditions set by the heterogeneity of the involved processes, stakeholders and institutions. Thus, this system level reveals the dependencies between the physical and the socio-economic system, which remain obscured at lower aggregation levels, but simultaneously this system level keeps in touch with the physical base, which may be lost at higher aggregation levels.

5.5. Emission control strategies in the physical system

At the start of the 21st century, an EU proposal to reduce high GWP refrigerant emissions from R+AC systems [European Commission, 2003] put the debate on the preferential strategy firmly on the political agenda. As noted, the physical system properties define two main strategies to reduce the climate impact from refrigerant emissions; *containment* of the refrigerant in the physical system (by integrated chain management) or *technology shift* towards using different (low-GWP) refrigerants or cooling technologies. Note that a technology shift in the R+AC sector has already been

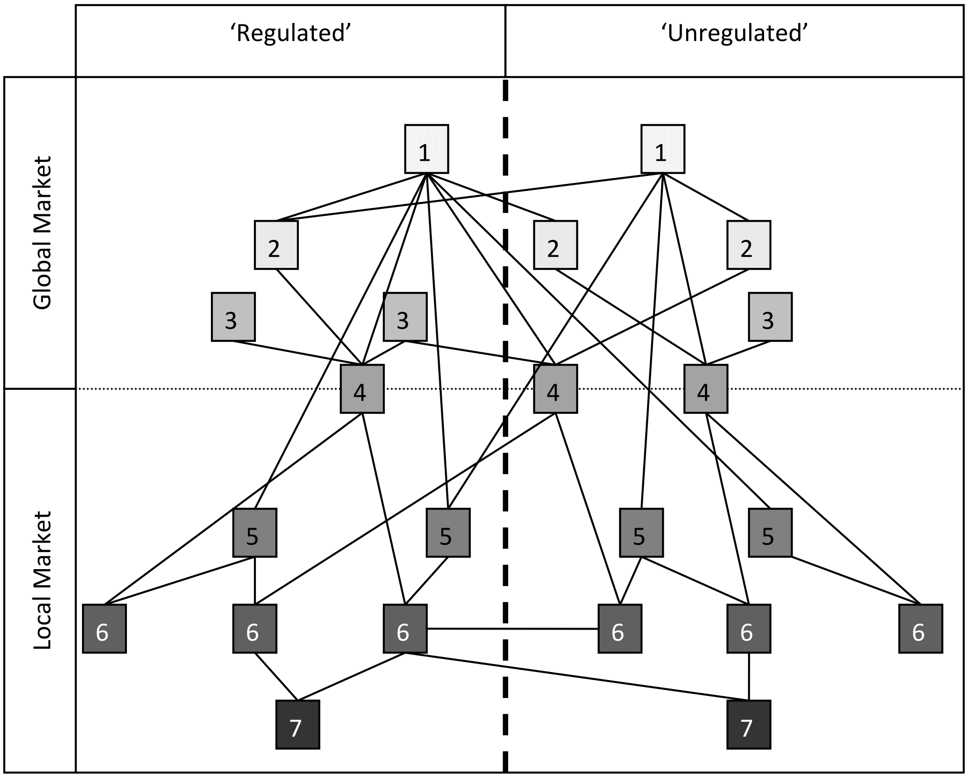

Figure 5.2 Schematic representation of the governance system of refrigeration and air conditioning systems. The processes depicted are the same as those in Figure 1. Squares represent individual processes with corresponding stakeholders. 1 Gas production 2 Foam production 3 Component production 4 System assembly / installation 5 Servicing 6 System operation 7 Disposal. Lines represent relations between different processes. The fat dotted line represents the boundary of national jurisdiction and separates 'regulated' and 'unregulated' territory. Processes 1-4 constitute the 'upstream' processes which operate in a global market, 5-7 constitute the 'downstream' processes, which operate in a local market.

forced once before through the Montreal Protocol. At the time of the Montreal Protocol implementation, the HFC-refrigerants currently in use were seen as the ideal alternatives to chlorinated refrigerants.

The debate principally revolves around the central argument of containability. One side argues that the use of high GWP refrigerants is principally no problem as long as the refrigerants are well contained within their system [Calm J.M., 2003; EPEE, 2001; European Commission, 2001]. Needlessly further limiting the number of available refrigerants (after the limitations by the Montreal Protocol) restrains business opportunities and can impair the optimization of R+AC systems, because system differentiation sometimes requires different refrigerants for optimal functioning [Calm, 2008; Wuebbles and Calm, 1997].

The other side argues that perfectly containing refrigerants within the systems is technically and institutionally infeasible [Johnson, 2004a] and therefore phasing out the use of high GWP refrigerants, is the only option to limit the environmental impact of R+AC systems in practice. Thus, one side promotes improving containment while continuing the use of high GWP refrigerants, whereas the other side promotes a technology shift towards low-GWP alternatives [European Commission, 2001]. Side arguments are brought into the debate to strengthen existing lines of reasoning, such as energy use, security, and costs of different alternatives.

Historically, the development of 'safe' and relatively cheap (chlorinated and) fluorinated high GWP refrigerants has contributed enormously to the expanding use of R+AC systems [Calm, 2008; Dauvergne, 2008]. The perceived lack of disadvantages to using these refrigerants led to a systematic 'lock in' to these substances. In the course of time, R+AC systems have therefore been optimized mainly on the physico-chemical properties of high GWP refrigerants [Calm, 2008]. This development and the resulting economies of scale have given producers of such systems a competitive advantage over producers of systems using different refrigerants or different technologies, now that the disadvantages of fluorinated refrigerants have (once more) become apparent. Switching to different technologies therefore requires considerable R&D and capital investments at the production level and may thus lead to higher prices for R+AC systems. In contrast, improving containment is thought not to require such substantial investments.

However, although improving containment can economically be considered a less demanding strategy, in practice effective containment requires an extensive institutional system [Willems and Baumert, 2003]. Responsible maintenance and disposal can only occur when the involved stakeholders possess sufficient information and required facilities exist within the governance system. Moreover, stakeholders involved in emitting processes may only be expected to follow through if they get sufficient incentive to do so (e.g. by penalties or financial incentive), which requires an effective monitoring and enforcement apparatus. Only a considerably developed apparatus can be expected to ensure compliance from all stakeholders in emitting processes in the physical system [Willems and Baumert, 2003]. Even though control would also be required in technology shift strategy, such strategy would require a much less organization, since the number of processes to be controlled would be much smaller.

Because physical restraints lead to unavoidable leakage in moving parts, joints or accidents, even an optimized maintenance regime is unlikely to totally prevent refrigerant emissions. Current emission rates in the EU, which has recently set regulation on containment are estimated in the order of 5-10% per year [McCulloch, 2009], although critics argue that emission estimates are generally too optimistic [Anderson, 2005; Johnson, 2004b]. Beyond this rate, system operators' control over system emissions may be limited due to the aforementioned physical restraints, especially in developing countries.

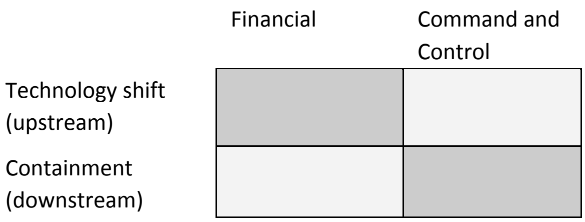

Figure 5.3 2x2 Matrix of policy instruments and policy strategies with corresponding stakeholders

5.6. Control strategies in the governance system: a 2x2 matrix of policy instruments and targeted stakeholders

The physical relations underlying the governance system imply that the two principal control strategies each require effectuation by a different set of stakeholders. Containment requires effectuation mainly by downstream stakeholders and technology shift requires effectuation mainly upstream. The choice for a control strategy thus simultaneously defines which stakeholder group is burdened with effectuating emission control. Political capacity for any strategy may be expected to depend on the fairness of burdening the targeted stakeholders. In environmental policy, the 'polluter pays' principle [OECD, 1995] is therefore often used to establish which stakeholders should be targeted. However, since upstream and downstream stakeholders principally share responsibility for system emissions (as discussed in section 5.3), each strategy may be considered fair.

Of the three principal types of policy instruments available to governments to manage processes in the socio-economic system (see e.g. [Klok, 1991; Van der Doelen, 1993]) only two are legally binding. Firstly, command and control instruments set legal process or product requirements to separate permitted and non-permitted processes, which, if properly enforced, prevent the operation of non-permitted processes. Secondly financial instruments apply (positive or negative) financial consequences based on process properties, in order to influence stakeholder preferences for alternative processes. Various 'soft' means to influence stakeholders operating processes also exist such as providing information or reaching voluntary agreements.

Each type of instrument may be used for either emission control strategy. Thus, a 2x2 matrix is created of policy instruments and policy strategies with the corresponding stakeholders involved (see Figure 5.3).

This section discusses the interaction between policy instruments and the principally targeted stakeholder groups. The different characteristics of different stakeholders and the processes they operate may influence each instrument's feasibility and possible effectiveness.

5.6.1. Stakeholder characteristics

Upstream stakeholders (the producers of fluorinated gases and of R+AC equipment) are often multinational corporations operating in multiple countries. These corporations are competing on the global market. Since regulation commonly results in higher costs, producers that face national regulation have competitive disadvantage over unregulated producers. These corporations can shift production towards countries that have less demanding environmental policy to avoid direct control over their production processes (causing 'carbon leakage') [Felder and Rutherford, 1993]. Since such course of action would not benefit the environment and only lead to economic losses in the legislating country, national governments are generally reluctant to implement measures that create such incentives [Schreuder, 2009b]. Moreover, the upstream stakeholders possess various power resources, such as informative advantages and economic capital, which they may use to try to pass down their responsibility to downstream stakeholders in order not to compromise their competitive position. Thus, directly targeting upstream stakeholders is generally difficult.

Downstream stakeholders (system operators, installation and maintenance personnel, disposal facilities) are generally bound to local processes and thus have no way to avoid direct control by shifting process location. Moreover they have relatively few power resources to affect policy implementation. Downstream stakeholders are thus in a dependent situation; they depend on products provided by upstream stakeholders, and on the regulation to which they are submitted. In any policy strategy, downstream stakeholders will bear costs; if upstream stakeholders are targeted, the costs of measures will likely be passed on downstream. If downstream stakeholders will be directly targeted, they face the costs directly.

5.6.2. The influence of the availability of actual process data on policy instruments

Actual emission-based instruments, such as a maximum emission allowance per system (command and control instrument) or a financial consequence per volume of emission (financial instrument) require the determination of actual emissions per process. This subsection describes how lacking data influences the opportunities for implementing policy instruments.

As noted, refrigerant emissions occur mainly during system operation, servicing and disposal. The volumes emitted during these processes are interrelated, since leakage during operation necessitates maintenance, and emission during disposal depends on the remaining refrigerant in the system. The exact volume of emission during each of these processes is generally unknown [Harnisch and Gluckman, 2001; Verwoerd, 2001]. Monitoring exact emissions would require an extensive administration for each system, which may be prohibitive especially for smaller systems with smaller refrigerant charges. National emission inventories are therefore based on trade statistics describing the flow of systems and refrigerant containers [IPCC, 2006]. Historically it was assumed that whatever refrigerant is used will eventually be emitted (so-called 'potential emissions'). Currently, another emission estimation approach is preferred in which the total refrigerant stock available in systems is estimated, to which a general emission rate is applied in order to estimate yearly emission. Apart from a general lack of data on refrigerant stocks in most countries, which complicates such estimation approaches, such generic approaches do not suffice to be able to attribute specific emissions to specific stakeholders, be it upstream or downstream stakeholders.

Neither financial nor command and control instruments can therefore directly target individual stakeholders based on their contribution to specific emissions. However, unlike many other emissions, refrigerants are functionally engineered specific purpose chemicals that are sold on the market; they are not 'waste products'. In line with the potential emission approach used for national emission inventories, financial instruments may therefore be aimed at refrigerant sales, rather than emissions. Through such an approach highly emitting processes, which require more refrigerants, will be affected more than less emitting processes. This will thus stimulate emission prevention, whether by technology shift or by containment. Such system could also stimulate recovery of refrigerant at disposal, if the stimulus would be sufficient to overcome the additional costs of a recovery system. However, since refrigerants are often contaminated with lubricant oil, the high costs of such recovery [UNEP, 2002] may be prohibitive and therefore additional measures would be required to stimulate recovery.

Financial instruments can thus in principle improve efforts at containment, since leakage would be financially unattractive. Moreover, financial instruments can stimulate development of alternative technologies, since alternative systems may become more financially attractive. However, the financial stimulus required to provide sufficient incentive may be relative large, as shown in the following example.

Assume that the stimulus would be comparable in size to the current price of carbon emissions on the European carbon exchange (about €15 per tonne). Then, the cost for potential emission of one kilogramme of R-134a (GWP 1410), which is the current refrigerant of choice in automobile air conditioning systems (MAC), would be €21. Although this means a 5-fold increase of current R-134a prices (~€5 per kg), the additional costs for air conditioning usage based on the amount of refrigerant used per car (~0.7kg) and their average leakage rate (10%/yr [Schwarz, 2001]) would be insignificant compared to the costs of purchasing and driving the car. Thus, to be effective to abate refrigerant emissions from MAC, the stimulus should be much larger than current carbon prices. Naturally, for larger systems with higher GWP refrigerants, higher leakage rates and smaller total usage costs, incentives may be more pronounced.

Potential emissions could also be the base for command and control instruments aimed at maximizing charges of specific refrigerants. However, unless refilling after leakage were prohibited (which is not feasible because the refrigeration or air conditioning system becomes useless if not sufficiently charged [Grace et al., 2005]), such approach would not control the actual volume of refrigerant emission. Therefore command and control instruments can not effectively set a maximum actual or potential emission. Instead, command and control instruments can ban specific refrigerants altogether based on their GWP and thus force a technology shift, or prescribe containment measures.

The lack of detailed process information further complicates implementing command and control instruments. Establishing a strictness of requirements that is both environmentally sound and technically feasible is a difficult task for policy makers. Since process details are often only known by the involved stakeholders, stakeholders have an informational advantage over policy makers, which they may use to influence policy making [Pettigrew, 1972]. Because upstream stakeholders are less abundant than downstream stakeholders, they possess more exclusive process information. Moreover, they generally represent more important economic interests and have more financial capacity to influence policy making in order to protect their interests. Thus, it may be more difficult to regulate upstream stakeholders than to regulate downstream stakeholders with command and control instruments. However, monitoring compliance is easier for regulations aimed at upstream stakeholders, since they constitute a smaller group.

Political influencing has been observed in the crafting of the Montreal Protocol, during which fluorinated refrigerant producers first opposed regulation and then embraced it when they had developed alternatives [Maxwell and Briscoe, 1997]. Similarly, mobile air conditioning (MAC) manufacturers have long argued against the EU’s effort to implement stricter regulation on MAC systems by claiming the impossibility to produce safe alternatives, but have, since implementation of the MAC directive [European Commission, 2006a], found several alternatives that seem to comply with these stricter rules [Calm, 2008].

5.7. Policy strategies and differences between industrial and developing countries

Different institutional requirements and financial consequences of the containment strategy and the technology shift strategy lead to possible barriers in effectuating control strategies in developing countries. In accordance with the 'common but differentiated responsibility' [UN, 1992a] and respective capabilities of industrialized and developing countries, developing countries are currently exempted from mandatory emission control. Emission control is generally though to interfere with their economic development, which has a higher priority. The requirement for investments may thus form a barrier for initiating a technology shift in developing countries. Simultaneously, a proper containment strategy requires a high degree of institutional organization, which is expected to be lacking in developing countries and may form an additional barrier for successful policy implementation [Caddy, 1997]. Thus, any strategy that involves additional costs or requires high institutional capacity is unlikely to be implemented by governments in developing countries until the socio-economic and political rift between developing countries and industrialized countries has been narrowed. As negotiated in UNFCCC, industrial countries are expected to implement climate policy 'unilaterally' at first. However, the crossing-border characteristics of the global marketplace open an indirect route to reduce R+AC emissions in developing countries, through regulation in industrialized countries.

As noted in the previous section, the globalized economy creates a situation in which it is difficult to directly regulate producers of fluorinated gas and R+AC equipment, in both industrialized and developing countries. However, since emissions occur primarily in downstream processes, direct regulation of upstream stakeholders is not necessary. Instead, by regulating the trade in final products, e.g. through product standards or taxation, governments can influence the type of products that can be put on the national market to be used by downstream stakeholders.

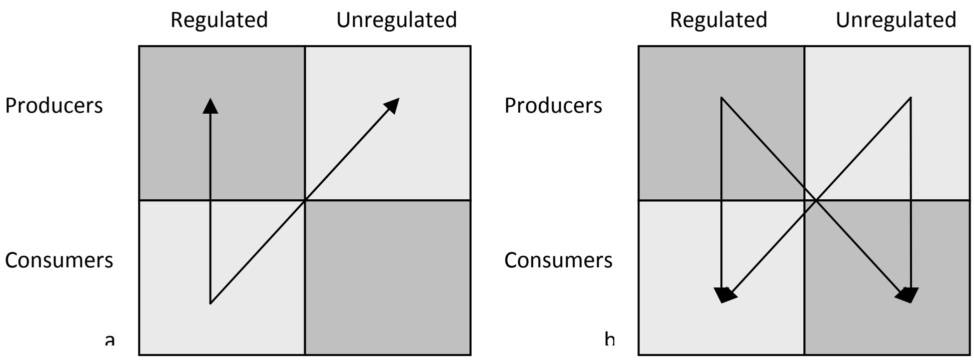

Figure 5.4 Interaction between consumers and producers in regulated and unregulated territory. Demand from regulated consumers may influence producers in both regulated and unregulated territory (fig a). Reversely, producers on the global market may influence consumption in both regulated and unregulated territory (fig b).

Table 5.1 Different opportunities for the strategy-instrument combinations in industrialized (Ind) and developing (Dev) countries

	Financial		Command and Control	
Tech shift (upstream)	Ind	±	Ind	+
	Dev	-/±	Dev	-/±
Containment (downstream)	Ind	+	Ind	+
	Dev	-	Dev	-

Produced goods can flow 'freely' through the global economy to reach consumers throughout the world. Therefore producers in 'unregulated' as well as 'regulated' territory may supply 'regulated' consumers. 'Unregulated' producers that supply regulated consumers will need to adjust part of their production processes in order to be allowed to sell products on the regulated market, similarly as 'regulated' producers. Product regulation thus implies an indirect (bottom up) route for technology shift by upstream stakeholders. Because of the globalized market for R+AC systems, such bottom up regulation therefore offers some opportunities for indirectly influencing stakeholders outside the regulated territory (see Figure 5.4).

Regulation may thus initiate technology development in regulated as well as unregulated territory. When global producers prefer uniform production processes over differentiated markets (as suggested in the position papers drafted at the introduction of EU regulation [European Commission, 2001]), regulation of part of the market could induce adjustment of production for the unregulated part of the market as well. However, as discussed above, the practical opportunities for such synergy are limited by the effects of market forces. Still, since unregulated stakeholders need to develop the required technology to access the regulated market, product requirements facilitate a possible future implementation of a similar policy in unregulated countries.

As such, national policies aimed at technological change at the production level, due to the globalized economy, can have a preparational function for a global governance structure. In order to speed up such a global regime, a technology shift in developing countries could be financed by (stakeholders) in industrialized countries, for instance through the global environmental facility (GEF) or the clean development mechanism (CDM). In contrast, organizational capacity building essentially needs to take place locally and is therefore more difficult to realize in developing countries. Policies that aim at downstream stakeholder effectuation therefore have no such preparational function. Table 5.1 summarizes the different opportunities for the various strategy-instrument combinations in industrialized and developing countries.

5.8. Overview of existing policy strategies

Throughout the industrialized world, various policies exist to reduce the climate impact from high-GWP refrigerant emissions from R+AC systems. As noted, such policies exist mainly in countries that have committed themselves to binding emission targets. This section describes seven policies that are currently implemented or being implemented: the Montreal Protocol (MP), the European F-gas regulation (EFR), the European MAC directive (EMD), the Austrian ban on the use of certain fluorinated gases (BAN), the Norwegian GHG tax (TAX), the Australian ETS (ETS) and the Clean Development

Table 5.2 Overview of the discussed regulations

Regulation	Short description
Montreal Protocol [UN, 1987]	▪ International agreement prohibiting consumption and production of ozone depleting substances (ODS), including refrigerants. National legislation to comply with the agreement generally bans the use of ODS in various applications. The strict limitations on production volumes directly influence refrigerant producers, the limitations on consumption influence equipment and foam manufacturers and installation and maintenance personnel.
EU F-gas regulation [European Commission, 2006b]	▪ Procedural regulation requiring leakage detection systems or regular leakage control of cooling applications with refrigerant loads above 3kg. The regulation also sets minimum demands for certification for installation and maintenance personnel. The regulation therefore targets the system operators and the installation and maintenance personnel.
European MAC directive [European Commission, 2006a]	▪ Restriction on using refrigerants with GWP>150 in mobile air conditioning systems from 2011 onwards in new models and from 2017 onwards for all new cars. The regulation principally targets car manufacturers, however indirectly it forces producers of MAC-systems and refrigerant manufacturers to cooperate in developing new technology in order not to lose part of their market.
Norwegian GHG tax [SFT, 2003]	▪ Taxation of refrigerants in systems and refrigerant containers based on their GWP. The regulation also regulates a refund scheme for controlled destruction of taxed refrigerants. The regulation targets system manufacturers, installation and maintenance personnel and disposal companies. Because price effects will be passed on, the operators of systems are also targeted.
Austrian ban on F-gas products [Austria, 2002]	▪ Restriction of installing new systems containing certain fluorinated gases. The regulation targets system operators, which can no longer buy certain systems. Indirectly it thus targets manufacturers that need to change production in order not to lose a market or market share.
Australian emission trading scheme [Australia, 2009]	▪ Requiring emission credits for potential emissions of fluorinated gases in products and refrigerant containers. Because Australia has no domestic production of fluorinated refrigerants, the scheme targets mainly the importers of these substances, both pure and within pre-filled systems.
Clean Development Mechanism Approved Methodology AM0071 [UNFCCC, 2009a]	▪ Credits for switching to low GWP (<50) refrigerants in production of domestic refrigerators. This regulation is the only one of the seven described regulations that offers a positive incentive for system adaptation since it results in revenue for change instead of costs. The regulation targets system manufacturers.

Mechanism AM0071 (CDM71). Table 5.2 describes each of the different regulations shortly. We do not elaborate on the details of each regulation, because such details depend on local and specific circumstances, whereas we aim to discuss possible contributions from these policies to global emission reduction in a more general way.

The studied policies can be categorized with the 2x2 instrument-strategy matrix described in section 5.6. As described in section 5.7, the institutional differences between industrialized and developing countries can lead to different opportunities for different strategy-instrument combinations. Therefore, such categorization enables a general assessment of the opportunities for successful introduction of these policies in developing countries.

The functional mechanisms in each policy may be characterized by its strategy (containment or technology shift), its corresponding targeted stakeholder group (upstream or downstream) and its instrument type (financial or C&C). Of the C&C instruments, the EU F-gas regulation aims to improve containment of refrigerants within their system. The Montreal Protocol, the MAC directive and the F-gas Ban aim to restrain the use of high GWP refrigerants as much as possible. Of the financial instruments, only the CDM AM0071 can be strictly categorized according to its strategy; it provides financial incentive to stop using high GWP refrigerants. The other two financial instruments (TAX and ETS) do not make a principal choice between strategies; they provide a financial incentive to reduce emissions, but leave it to the stakeholders to arrange the system in the most cost-effective way. In combination the seven policies cover each quadrant of the instrument-strategy matrix (see Table 5.3).

Combining Table 5.1 and Table 5.3 leads to a general assessment of each policy's possible contribution to emission governance in developing countries. Our analysis of the four instrument-strategy combinations in the 2x2 matrix found that successful effectuation of emission control policy in developing countries is difficult for most of the quadrants. Institutional shortcomings complicate containment policies, because such policies need to be aimed at downstream stakeholders, the control of whom, due to their large number, needs considerable institutional capacity. Simultaneously, financial mechanisms that raise the price of given products, and thus may restrain economic growth, are seen as politically undesirable, because economic growth is the main priority in developing countries. Therefore, policies in three out of four quadrants seem to have limited merits for emission control in developing countries.

Table 5.3 Position of studied policies in the 2x2 matrix

	Financial	Command and Control
Tech shift (upstream)	CDM71 TAX ETS	EMD BAN MP
Containment (downstream)	TAX ETS	EFR

Only policies aimed at technology shift by C&C therefore seem to be able to influence governance in developing countries, albeit indirectly. Of the studied policies, only the MP,BAN and EMD can be characterized as such. However, CDM71 may also escape the mentioned barriers. In the CDM the financial burden for technology shift is not carried by developing countries, but by the investors in industrialized countries and does thus not encounter the economic barrier in developing countries. Although some institutional capacity is required to successfully register CDM projects, the AM00071 does not require a massive control apparatus, since only relatively few producers are involved. Thus, technology shift for R+AC systems could possibly also be induced through such CDM approaches.

5.9. Discussion

5.9.1. Emission control from a long term perspective

In order to stabilize atmospheric GHG levels, the ultimate global emission rate can only be as high as the rate of global reuptake and atmospheric destruction. Some emission trajectories that seek to limit global warming to below 2ºC above preindustrial temperature even require 'negative emission' rates at the end of the 21st century [IPCC, 2007]. Natural reuptake is estimated at around 7Gt CO_2/yr [IPCC, 2007], which leaves only a relatively small remaining GHG budget compared to the 2004 global emissions of around 49Gt CO_2-eq/yr [IPCC, 2007]. Successful long term governance should aim to keep total emissions from the physical system within the available budget. Although growing emissions from some socio-economic sectors may be compensated by reduced emissions elsewhere for some time, it is not likely that emissions from any sector can be allowed to continue increasing indefinitely. To compensate for the growth of the number of processes, the emission per process (or, in this case per refrigeration or air conditioning system) needs to be systematically reduced in the future.

As noted earlier, containment strategies may be expected to run into physical barriers that prevent systematically reducing emission per system. Although dependent on the exact physical limits and the consequent R+AC sector emissions, it seems unlikely that leakage reduction can fully compensate for the expected growth in the number of R+AC systems globally. Moreover, as discussed in section 5.7, containment strategies are less likely to be able to effectively reduce leakage to the physical limits in developing countries. Thus, a containment strategy is unlikely to reduce global emissions from R+AC systems below the current rate in the future. Furthermore, it seems highly unlikely that refrigerant emissions can, socially nor economically, be allowed to constitute such an important share of the future (severely limited) global GHG budget.

Only the MP and BAN policies set strict limits to refrigerant emissions over time, since they fully eliminate the use of (certain types of) high GWP refrigerants[3]. Still, as these policies typically target specific substances only, the introduction of unregulated substitutes should be monitored closely to prevent problem shifting to different environmental impact categories (as becomes clear from the MP experience) or even resurfacing of similar problems in a new disguise (such as the possible introduction of high GWP HFPE-refrigerants to replace HFC-refrigerants [Sekiya and Misaki, 2000; Tsai,

[3] ODS refrigerants in the case of MP

2007]). The only other approach that theoretically limits the total emission budget within its jurisdiction is ETS. However, since such approach is not expected to be feasible in developing countries, it cannot limit total system emissions. Other policies require continuous adjustments in reaction to expected socio-economic growth leading to more R+AC use.

5.9.2. Providing incentive for technology shift

Realizing lower future emissions from the R+AC sector within the limits of the available emission budget therefore probably necessitates a technology shift. Since a technology shift implies involvement of upstream stakeholders, successful long term policy needs to create an incentive for upstream stakeholders to develop acceptable technological alternatives. The opportunity to create such incentives differs for command and control instruments and financial instruments.

Financial instruments can influence the market price of R+AC systems based on their emissions. If each amount of additional emission leads to additional costs, there is an automatic continuous incentive for stakeholders to reduce the amount of emissions per system to achieve a better competitive position, especially if life cycle emissions are included in the purchase price. As noted earlier, the strength of the incentive depends on the specifics of the regulation, i.e. the costs attached to emissions need to be sufficiently high.

For command and control instruments, the incentive can only be generated by continuously tightening product requirements. After all, command and control instruments basically have a binary function; if a product complies with the regulations there are no direct benefits to further improve its properties. Figure 5.5 shows the different incentive structure for command and control and financial instruments. To avoid delay at implementation and prevent uneconomic depreciation of investments in 'obsolete' technologies, any new requirements need to be set with sufficient advance notice. The information disadvantage discussed earlier may complicate establishing such future stricter requirements ahead of time. Uncertainty about the required strictness, due to uncertainty in the development of the number of processes, and uncertainty about the technical feasibility of such strict requirements, due to information

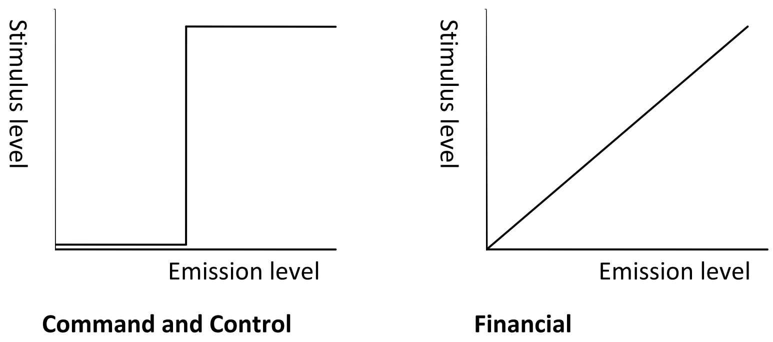

Figure 5.5 Incentive structure for command and control and financial instrument type.

disadvantages, could restrain policy makers from setting targets that provide sufficient incentive to continuously develop improved processes and thus delay or impair the necessary course of action. Nonetheless, the history of the Montreal Protocol and the more recent example of the MAC directive show the resilience of stakeholders in complying with mandated requirements once they are set and show that uncertainty in developments nor technological feasibility needs to be a barrier for implementing future command and control requirements.

The debate on refrigerants shows strong parallels with the development of policies for other hazardous substances, such as the dispersion of pesticides, especially considering the expected rapid increase in the use of R+AC systems in developing countries. As long as hazardous substances are used within a controlled environment in which they can be collected, collectively treated and possibly recycled, and in small enough quantities so that for the remaining emissions environmental degradation of the substance is faster than accumulation, the environmental damage is limited. However, when such usage controls are lifted, as in the case of the expiry of the patent on diclofenac and its subsequent massive dispersive use as an anti- inflammatory drug in feedstock in developing countries [Hopkin, 2006; Oaks et al., 2004], accumulation can occur with dramatic environmental consequences. In contrast to the relatively localized consequences of local emissions of pesticides to soil, groundwater or atmosphere, the consequences of uncontrolled GHG emissions from local R+AC systems has global consequences.T

he current chapter discusses the global governance of R+AC systems at a highly aggregated level, which leads to highly generalized conclusions. Large differences exist in the described physical systems; obviously, different types of systems offer different opportunities for technology shifts and may also have different physical restraints in optimizing containment. Also, large differences in institutional capacity exist within the groups of developing countries and industrialized countries. The conclusions should therefore be interpreted as input to the general discussion on global climate policy regarding fluorinated gases. Although the conclusions may be relevant also at a more specific country level or technological system level, country or technology specific discussion should take into account the more detailed information available at such levels.

5.10. Conclusion

The growing global demand for refrigeration and air conditioning systems is expected to lead to an increasing emission of high GWP refrigerants. Such development runs counter to the effort to reduce global GHG emissions in order to prevent catastrophic climate change.

Several regulations are being or have been effectuated to reduce high GWP refrigerant emissions in various industrialized countries. However, national policies may have limited effects outside their jurisdictional borders. Global warming can only be controlled by controlling emissions from all processes throughout the world; partial emission control is therefore not a long term effective solution.

Principally, a patchwork of national policies could cover the refrigerant emissions from R+AC systems globally. However, the global market nature of the production processes in the R+AC product system generally leads to preference for a uniform global governance framework to avoid trade conflicts. Still, different political and socio-economical circumstances exist around the world. These circumstances may affect the possible effectiveness of different control options. Notably, developing countries generally exhibit political prioritization of economic growth over climate policy and often have a smaller institutional capacity for control and enforcement. Assessment of possible long term strategies to control the impact of refrigerant emissions should therefore account for these cross-national differences. In this study, we have assessed which contribution each of seven current policies can make to global control of high GWP refrigerant emissions, by constructing and analyzing the related governance system.

We conclude that from this governance systems' perspective, containment strategies may be expected to function effectively only in organized (industrial) countries that have put climate policy high on the political agenda. Containment policies, which typically involve downstream stakeholders, require institutions to provide information and to responsibly manage disposal products, which may not be expected to be function effectively in developing countries. Moreover, in the case of command and control instruments, containment requires sufficient institutional capacity for control and enforcement which is generally lacking in developing countries. In the case of financial instruments, control is also necessary and such policy is expected to lead to lower economic growth which is generally not preferred in developing countries.

Technology shift strategies may have higher merits in developing countries. Such strategies typically involve producing stakeholders, which generally operate on the global market. Financial instruments for these stakeholders are probably only effective if implemented globally, because local regulation could trigger production relocation to unregulated countries. The reluctance of developing countries to implement policies that restrain economic growth, may restrict such policy options, although this depends on whether the policy would effectively mean taxing unwanted technologies or subsidizing wanted technologies.

Command and control instruments to induce technology shift basically imply setting minimal product standards. Principally, standards that lead to increased product costs are less likely to be implemented in developing countries because of economic priority. However, standards that are implemented in industrialized countries force global stakeholders to develop the required technologies and adjust part of the production capital. These investments and their downward effect on production costs due to learning curve and economies of scale, may bring producers over the tipping point at which changing the entire production capital may be more efficient. In this way, it can facilitate technological leap-frogging in developing countries. Thus, command and control instruments may lead to technological change in both industrialized and developing countries.

Moreover, even if instruments aimed at technology shift do not lead to crossing such a tipping point, at least they build technological and informational capacity at the relevant stakeholder level, which can lead to a rapid transition when the jurisdictional border of such policies would be expanded to developing countries. Such learning effect does not take place for instruments aimed at downstream stakeholders. Focus on such instruments in industrialized countries thus does not facilitate technological leap-frogging for developing countries.

Our final assessment compares each of the seven studied policies with these findings in order to assess their possible contribution to a global solution for refrigerant emissions. We conclude that the Montreal Protocol, the MAC directive, the Ban on fluorinated substances, and CDM AM0071 are policies that could be valuable to reduce high GWP emissions on a global governance scale. They lead to the development of technologies that can also be used into developing countries, although substantial capital investments may be required to facilitate this. CDM AM0071 provides a positive means to effectuate such technology shift in developing countries, as industrialized countries pay for the CDM credits it generates and it thus does not burden developing countries financially. ETS and Tax scheme are valuable insofar as they provide incentive for developing alternative technologies, but may require too much organization to be implemented globally and be valuable as a means to improve global responsible containment. The EU F-gas directive is expected to be of little merit outside its jurisdictional borders and may be expected to require too much institutional capacity to be expanded into developing countries.

Finally we conclude that, apart from not being a global solution for the reasons described above, a containment strategy is not likely to be an effective long term solution because feasible reduction rates are unlikely to be able to compensate for increasing use of R+AC systems globally. Thus, policy makers should clarify that current measures to reduce emissions by improving containment should be considered temporary solutions and aim at providing incentives for upstream stakeholder to effectuate a technology shift that can provide safe and secure cooling without using high-GWP refrigerants in the future.

6. INDICATIONS FOR A CHANGING ELECTRICITY DEMAND PATTERN: THE TEMPERATURE DEPENDENCE OF ELECTRICITY DEMAND IN THE NETHERLANDS[1]

Abstract *This study assesses the electricity demand pattern in the relatively temperate climate of the Netherlands (latitude 52º30'N). Daily electricity demand and average temperature during the period from 1970 until 2007 are investigated for possible trends in the temperature dependence of electricity demand. We hypothesize that the increased use of cooling applications has shifted the temperature dependence of electricity demand upwards in summer months. Our results show significant increases in temperature dependence of electricity demand in May, June, September, October and during the summer holidays. During the period studied, temperature dependence in these months has shifted from negative to positive, meaning that a higher temperature now leads to an increased electricity demand in these months, rather than a decreased demand as observed historically. Although electricity demand in countries with moderate summer temperatures such as the Netherlands generally peaks in winter months and shows a minimum in summer months, this trend may signal the development of an additional peak in summer, especially given the expected climatic change. As power generating capacity may be negatively influenced by higher temperatures due to decreasing process cooling possibilities, an increasing electricity demand at higher temperatures may have important consequences for power generation capacity planning and maintenance scheduling.*

[1] This chapter is a slightly adapted version of Hekkenberg, Benders, Moll and Schoot Uiterkamp (2009). *Indications for a changing electricity demand pattern: the temperature dependence of electricity demand in the Netherlands.* Energy Policy 37:1542-1551. doi:10.1016/j.enpol.2008.12.30.

6.1. Introduction

Daily electricity demand in countries throughout the world shows a clear seasonal pattern. Three different seasonal patterns may be observed in general; average daily electricity demand may peak during winter, during summer, or both, in which case either the winter or the summer peak is highest. Two of these patters can be found in Europe (see Figure 6.1). Average daily electricity demand in most EU-15 countries, amongst which the Netherlands, historically shows a single peak during winter months [Eurostat, 2008]. Only Spain, Portugal, Italy and Greece show an additional peak during summer months. Demand patterns with only summer peaks may be found outside of Europe, e.g. as observed in Bangkok [Wangpattarapong et al., 2008] and Hong Kong [Al-Zayer and Al-Ibrahim, 1996].

The seasonal pattern results from the fluctuating influx of solar radiation and the varying economic activity throughout the year in the Northern hemisphere [Pardo et al., 2002]. Winter peaks in electricity demand may be attributed to increased lighting demand because of shorter daylight periods as well as to an increased heating demand and a higher average economic activity in winter than in summer due to holidays. Summer peaks are usually attributed to the use of electric cooling applications such as fans and especially air conditioners.

Time series analysis of monthly electricity demand in Spain, Portugal, Italy and Greece shows that the relative importance of electricity demand during summer months has been increasing over the last decades, resulting in a summer peak average demand that topped the winter peak in Greece, Italy and Spain in 2006 (Figure 6.2). This development is reflected in studies by Valor et al [2001] and Moral-Carcedo and Vicéns-Otero [2005], who correlate the Spanish daily electricity demand between 1980 and 1998 to outdoor

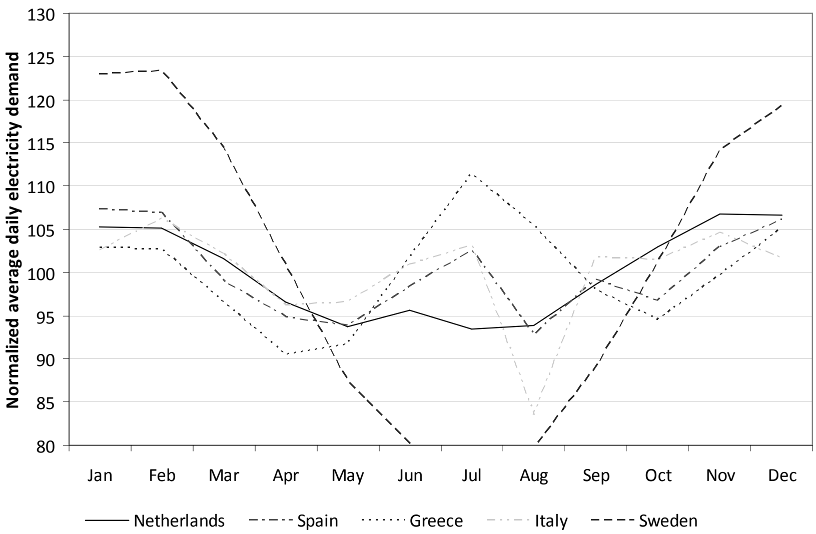

Figure 6.1 Seasonal variation in daily electricity demand in several EU-15 countries over the period 1986-2006. Average daily electricity demand = 100 for each country. Data adapted from [Eurostat, 2008]

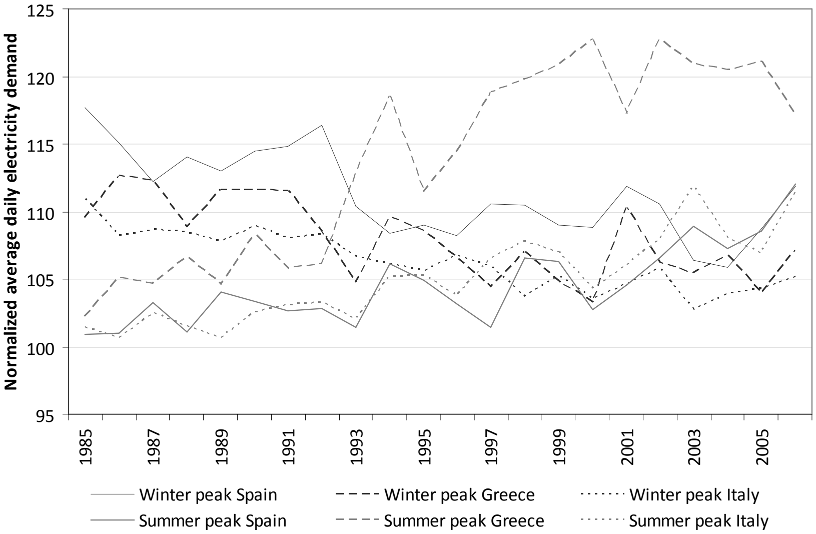

Figure 6.2 Development of the average daily electricity demand in the peak summer and winter months in Greece, Italy and Spain from 1986 to 2006. Annual average daily electricity demand = 100 for each year and each country. Peak months are determined for each year as the summer (April – September) and winter (October-March) month with the highest average daily electricity demand in each given year. ***Data adapted from [Eurostat, 2008]***

temperature and by Bessec and Fouquau [2008] for all EU-15 countries. Their studies, like others [Franco and Sanstad, 2008; Mirasgedis et al., 2007; Nobel, 1996; Pardo et al., 2002; Ruth and Lin, 2006; Sailor and Muñoz, 1997], find a 'u' shaped relation between outdoor temperature and electricity demand. However, they find that in recent years, the positive correlation between electricity demand and outdoor temperature for temperatures upwards of 18ºC is becoming more pronounced. This development is thought to mainly result from the increasing use of cooling applications at high temperatures.

Electricity demand from cooling applications is logically expected to be positively temperature dependent: cooling uses more electricity on warmer days. Three mechanisms are principally accountable for this dependence. Firstly, at higher outdoor temperatures, a larger temperature difference needs to be overcome, thus increasing the cooling load. Secondly, higher temperatures lead to less efficient heat exchange in cooling applications, therefore more vapor-compression cycles have to be made to exchange the same load of heat. Thirdly and probably most obvious, people are more inclined to turn on air conditioning applications on warm days than on cold days.

However, not only countries with summers generally considered 'warm' or 'hot' show a societal trend towards increased use of cooling applications. The use of cooling applications has also increased in countries at higher latitudes with generally moderate summer temperatures, such as the Netherlands (latitude 52º30'N); supermarkets have generally increased their area of cold products over the last decades, while most new commercial and office buildings are being equipped with air conditioning applications [Van Arkel et al., 1999]. Relatively little is known about the effects of cooling on electricity demand in the Netherlands. An exploratory study estimated total electricity demand from cooling applications in the Netherlands to be 4-5 TWh in 2003 [Pennartz, 2005], which equals 4-5% of total electricity demand [CBS, 2008]. Still, the Dutch monthly electricity demand pattern does not show a summer peak such as seen in 'warm' countries. Nonetheless, an increasing use of cooling applications is expected to lead to an increasingly positive relation between temperature and electricity demand. Apparently, this effect is obscured in the monthly figures by other (socio-economic) drivers such as the generally lower economic activity during summer due to holidays. The only known publication that correlates outdoor temperature and electricity demand for the Netherlands [Nobel, 1996] does not investigate historic development, although it does find a positive relation between average daily temperature and minimum electricity demand in the following night for average day temperatures above normal[2].

However, temperature dependence patterns are important for assessments of future electricity demand, especially in the context of climate change [Amato et al., 2005; Isaac and Van Vuuren, 2009; Ruth and Lin, 2006; Sailor and Pavlova, 2003]. Possible trends in such patterns may thus improve such assessments. Moreover, a changing temperature dependence may be a first indication of the development of an (initially small) summer peak, after all, such a trend may result in an increasing importance of summer months in the yearly total. Furthermore, a changing temperature dependence may have implications for maintenance scheduling. This study therefore aims to disclose the effect of an increased use of cooling applications on the Dutch electricity demand.

6.2. Methodology

We have collected daily data on temperature and electricity use, and analyzed the resulting data points with temperature as the independent variable and electricity use as the dependent variable. Unfortunately, there is a high degree of noise in such data because of daily variation in electricity consumption unrelated to temperature differences. Such noise in the data may obscure any existing trend in small data samples.

Therefore, studies investigating temperature dependence of electricity demand usually analyze time series of a year or longer, and distill long-term trends such as economic growth or population dynamics using extensive data mining techniques. Such approaches generally require formal assumptions about the various trends that may exist in the time series. In case the appropriate parameters are included in such an analysis, such approaches could possibly find a sophisticated description of the observed temperature dependence, perhaps even throughout the years. However, in our view the underlying socio-economic variation is too complex to adequately capture in formal assumptions, and our data sample is not sufficiently consistent (see 'data' section) to allow a comprehensive analysis. Therefore we have not followed a complex data mining approach.

Instead, we have deliberately chosen a relatively simple approach that uses the raw data available to establish a possible trend in temperature dependence regardless of all other trends. After all, our primary aim is to find evidence that the temperature dependence may be subject to change, not to establish a sophisticated formula to describe temperature dependence. Instead of aggregating available data into yearly or larger

[2] Nobel refers to normal temperatures as 2-18 °C

datasets, we have separated the available data into monthly sets to describe the temperature dependence of electricity demand in the months from 1970 until 2007 for which suitable data was available.

For each working day in each month we have calculated the deviation of daily electricity use relative to the average daily electricity use on working days in the same month. We have subsequently plotted the relative deviation of electricity use for each day against the average temperature on that day. For each of the resulting scatter plots we have calculated an ordinary least squared linear regression coefficient. Each regression coefficient represents the temperature dependence of electricity demand for a particular month in a particular year. Negative coefficients mean that a higher temperature leads to lower electricity demand, positive coefficients mean that a higher temperature leads to higher electricity demand. Through this approach, we have collected a time series of temperature dependence coefficients for each month of the year. In this way, observed trends throughout the time series represent changes in the temperature dependence of electricity demand. Finally, observed trends are analyzed statistically to test the robustness of the findings.

The main advantage of this approach is that it compares the deviations within one month, which result in dependence coefficients that are representative for that particular month. Such an approach diminishes the possible distortive influence of inconsistent seasonal parameters such as relative economic activity and solar radiation of which the combined effects are hard to estimate, and of possible methodological changes in measuring electricity demand or temperature. Provided that the data within the month are (more) consistent, this possibly results in clearer temperature dependence signals. A disadvantage is that the results are harder to interpret because it will not result in a 'general' temperature dependence of electricity demand.

Trends found within these short time series can be highly dependent on single observations. For example, the chance occurrence of a relatively low electricity demand on a day with relatively high temperature may pull the observed trend downwards, whereas if a low demand occurred on a day with a relatively low temperature the trend would be pushed upwards. Because of the noise in the available data, each separate dataset is relatively sensitive to such chance occurrences.

Part of the temperature independent noise may be anticipated, such as general economic activity differences between working days and non-working days. The difference between working days and non-working days shows clear patterns that can account for a large share of day to day variation in electricity demand [Moral-Carcedo and Vicéns-Otero, 2005]. Eliminating this variability can contribute to extracting the signal we are looking for. We have therefore focused our research on working days only. Box 6.1 describes the 'non-working days' which have been excluded from our study. The average deviation of electricity demand on excluded data compared with the corresponding monthly average electricity demand on included data is -20.7%, suggesting that electricity demand on excluded days differs from that on included days indeed. By excluding non-working day observations we lose information on the temperature dependence trend on non-working days. However, non-working days cannot be regarded as a homogenous group. Saturdays differ from Sundays, and each holiday may again have its own characteristics. Therefore researching a trend in non-working days would require further specification of the type of non-working day. Since we have chosen to analyze the data

Box 6.1 'Non-working days'

The following days are excluded from our study.

1) Weekends (all Saturdays and Sundays)

2) National holidays (New Years Day, Good Friday, Easter day and Easter Monday, Queens Day (April 30th, except when on Sunday), Ascension Day, Whit Sunday and Whit Monday, Christmas Day and Boxing Day, New Years Eve).

3) Christmas holiday (all dates between and including 24 December and 2 January)

4) Single days that are preceded *and* followed by weekends or holidays (e.g. Friday after Ascension Day).

Two other days have been excluded (September 5th 1973 and December 17th 2003), because on these days the deviation of the reported electricity use from the monthly average exceeded 20% for no apparent reason. It is assumed that these are "contaminated" data points.

Following these exclusion rules leads to the exclusion of 3972 (32.0%) of 12410 available data points. All other data points have been included.

on a monthly data for the reasons described above, there are too few observations of each non-working day type per month to make a meaningful analysis.

Still, our generic exclusion rules do not totally suppress the data noise. Because differences in electricity demand resulting from the temperature dependence of electricity demand may still be small relative to remaining noise, the findings within separate datasets have little individual meaning in themselves. Therefore, conclusions about the possible trends in temperature dependence should not be based on individual datasets, but only on their combination.

6.3. Data

We analyzed the relation between outdoor temperature and electricity demand on the Dutch high voltage network during the period 1970 – 2007. We therefore collected data on daily electricity load and daily outdoor temperature during this period.

6.3.1. Electricity data

Our data on electricity load consist of two separate datasets. We obtained historic half-hourly electricity load figures for the period January 1970 to May 1999 from the current Dutch Transport System Operator (TSO) TenneT. This dataset ('SEP dataset') consists of the historical measurement data from the cooperation of electricity producers (SEP), which measured average electricity load on the high voltage network during 5 minute periods for each half hour. TenneT was formed from SEP in 1998 as the independent TSO in the Netherlands conform the new policy of a liberalized electricity market. Unfortunately, electricity load data during the first years after the reform are not available. From 2003 onwards, electricity load data for 15 minute intervals is available on the internet [TenneT, 2008]. We have used these data ('TenneT dataset') from March 2003 up until December 2007. Because of the missing data, the combined dataset therefore covers a total of 411 months in the period 1970 to 2007; 34 or 35 datasets are available for each month of the year.

Comparison of the two datasets thus obtained shows that the SEP dataset does not fit the TenneT dataset. The difference is thought to originate from a changed measurement method between both datasets. The SEP-dataset consists of the measured load at the connections of the regional grids with the high voltage grid and centrally operated production facilities (operated by SEP). The TenneT dataset is the sum of data provided by each grid administrator, which reports on each connected party with a generating capacity of more than 10 MW [TenneT, 2008]. Therefore, the TenneT dataset may include some decentralized sources that were excluded in the SEP dataset. Furthermore, comparison of both datasets with total Dutch electricity available through the public grid as calculated by Statistics Netherlands (CBS), shows that the SEP dataset progressively deviates from the data reported by CBS. The SEP dataset covers 99% of the total electricity available through the public grid in 1976-1986 but the coverage declines to only 83% in 1998 (Figure 6.3). This trend may be partly explained by an increasing share of decentralized electricity production in local grids that was not transported through the high voltage gridlines measured by SEP. The TenneT dataset seems to be closing this 'gap', possibly because the grid administrators currently reporting electricity demand may include such data in their reports.

The inconsistency between the reported values in the SEP dataset and the TenneT dataset and their discrepancy compared with CBS total electricity consumption data complicates the comparison of electricity load over the years. However, the described changes in measurement methodology and altered economic structure that result in this discrepancy are expected to have resulted in long term rather than short-term data variance. Our analysis analyzes absolute values only within a one month timeframe. It therefore does not compare absolute values that are far apart in time, nor values coming from different datasets. Only after this initial processing of the data, the data are

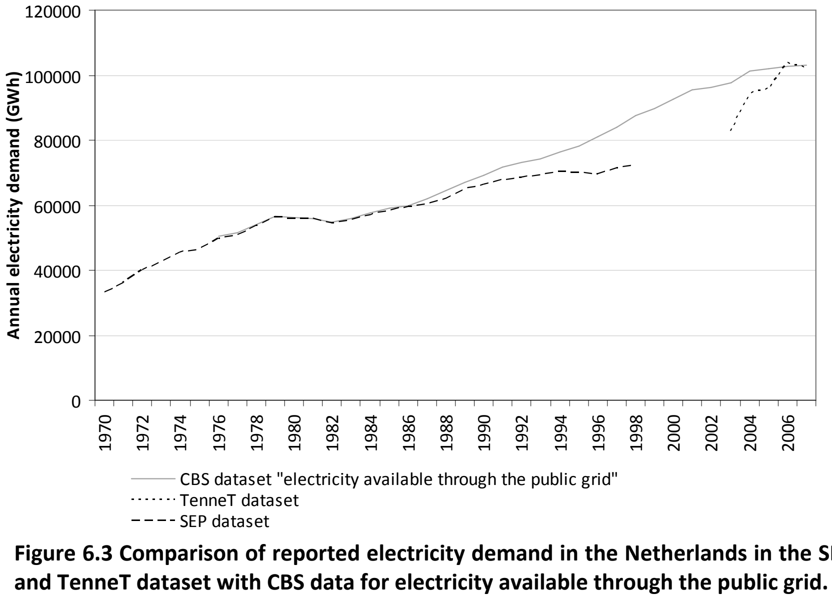

Figure 6.3 Comparison of reported electricity demand in the Netherlands in the SEP and TenneT dataset with CBS data for electricity available through the public grid.

compared with data from other months, thus reducing the distortion arising from using separate datasets.

6.3.2. Temperature data

Daily temperatures may vary throughout the country, mainly related to the proximity of the North Sea and the prevailing wind direction. To account properly for these variations, our temperature indicator would ideally average temperatures throughout the country, weighted by relative share in national electricity consumption, which may be influenced by e.g. local population density and local economic structure. The Royal Dutch Meteorological Institute (KNMI) publishes historical daily weather data for ten different measurement stations on their website [KNMI, 2008], but publishes no average value nor a methodology to calculate this. Considering the required effort of determining each measurement station's relative weight compared to the expected added accuracy of the temperature indicator we decided to use only the data for the measurement station in De Bilt (station 260). De Bilt is a town centrally located in the Netherlands, and close to the highly populated Randstad region; it is therefore believed to be suitable as a proxy for population based average temperature in the Netherlands.

6.4. Results

Figure 6.4 and Figure 6.5 show examples of two of the scatter plots we have plotted for the 411 monthly datasets. They show the percentage deviation from average monthly electricity demand on each working day in June 1976 and June 1996 plotted against the average day temperature on each of those working days. Each graph also shows the regression line found to best fit the observed data, based on an ordinary least square linear regression. The regression coefficient for the predictor (temperature) can be

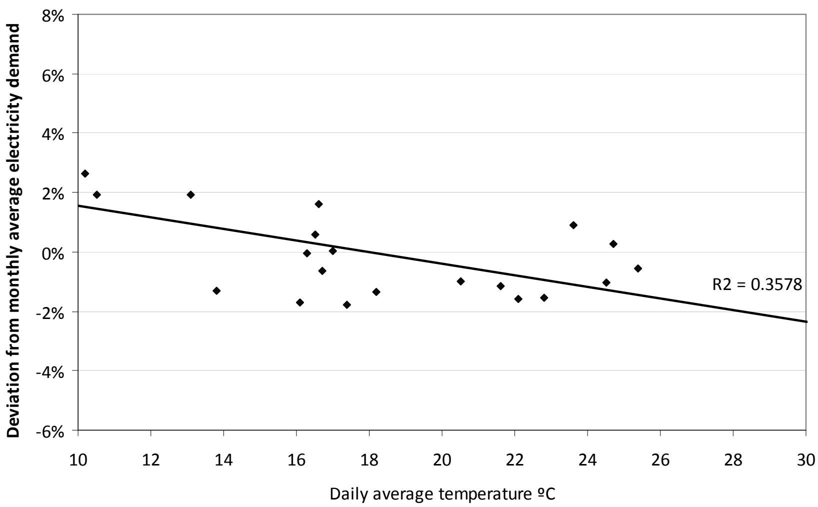

Figure 6.4 Percentage deviation from average electricity demand on each working day in June 1976 plotted against the average temperature on that day

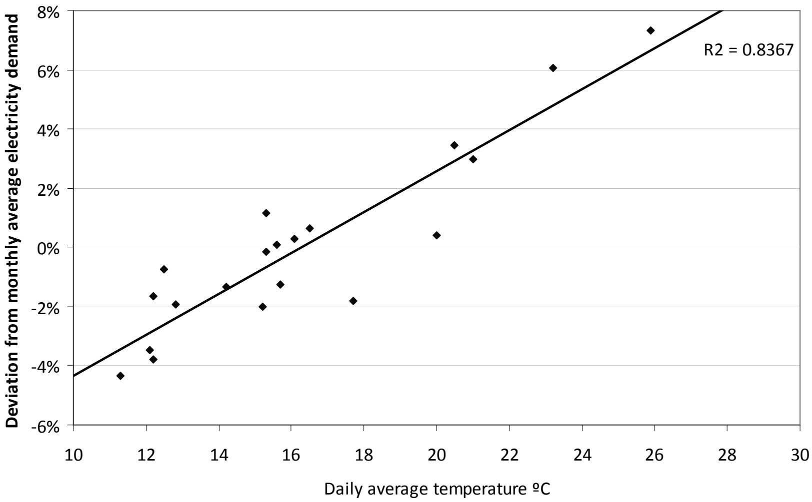

Figure 6.5 Percentage deviation from average electricity demand on each working day in June 1996 plotted against the average temperature on that day

regarded as an indicator for the temperature dependence of electricity demand during that month. The coefficient measures the relative deviation of the average monthly electricity demand per degree of temperature change. Negative coefficients, visible as downward sloping regression lines, indicate that in the observed month, a higher temperature correlates with a lower electricity demand. Positive coefficients indicate that a higher temperature correlates with higher electricity demand. As mentioned earlier, little value should be assigned to each individual graph, since each separate dataset is relatively vulnerable to random occurrence of distorting noise.

Figure 6.4 and Figure 6.5 return in miniature in Figure 6.6, which shows all 411 scatter plots for the 411 datasets. The combination of graphs in this figure shows the full time series of the 411 months from January 1970 to December 2007 for which data was available. It also shows the linear regression functions that best fit each of the 411 separate data sets. Figure 6.6 reveals a clear trend from downward sloping regression functions (negative coefficients) to upward sloping regression functions (positive coefficients) for several months throughout the time series. This trend is most clearly visible for the months May and June, but is also found for September and October. The months from November to April show mainly downwards sloping regression functions. The summer months July and August show a rather chaotic pattern, of alternating upwards and downwards sloping functions.

Further analysis of the temperature dependence coefficients reveals that coefficients in May, June, September and October did not only turn from negative to positive over the 37 year long period, but show a clear progression over time (Figure 6.7). This finding means that electricity demand in May, June, September and October is increasingly depending on temperature differences, whereby higher temperatures lead to increased electricity demand. The observed trend suggests that a temperature difference of 1 °C in May, June, or September would currently result in a deviation of total Dutch electricity demand in these months of over 0.5%.

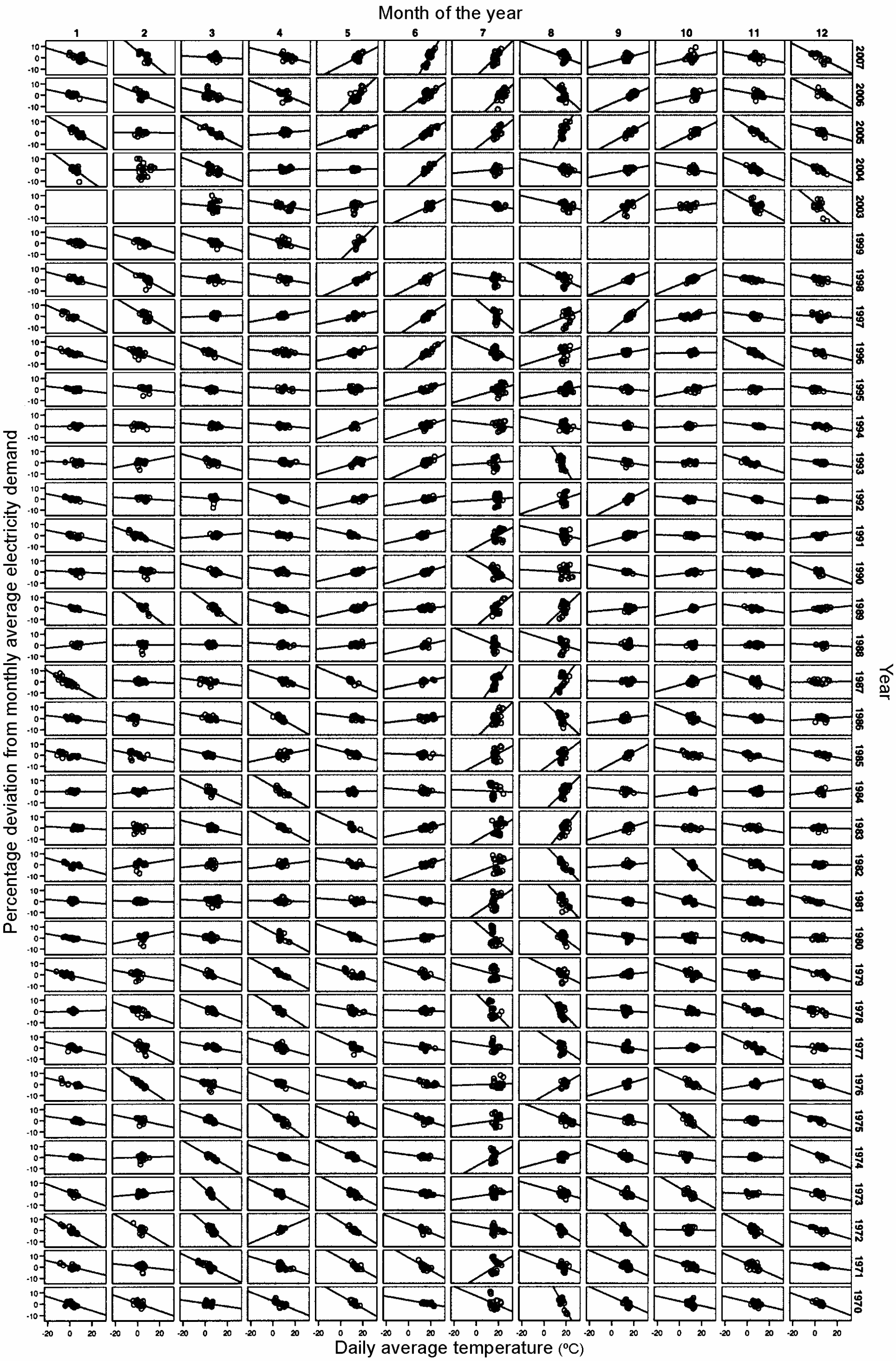

Figure 6.6 (Caption on next page)

Figure 6.6 Percentage deviation from average monthly electricity demand on each working day plotted against the average temperature on that day as in figures 4 and 5, for all 411 months from January 1970 to December 2007 for which data was available. Months are plotted from left (1=January) to right (12=December), years are plotted from bottom to top. Following the months May and June throughout the time series reveals a clearly shifting regression line. Note that regression lines in each individual graph are not tested for significance and generally have a low R^2.

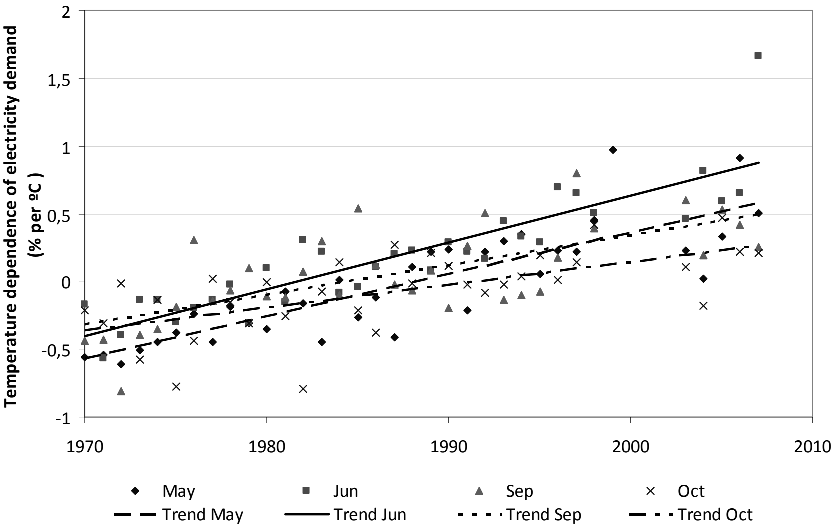

Figure 6.7 Development of temperature dependence coefficients in May, June, September and October in the Netherlands from 1970 to 2007.

Table 6.1 Regression statistics for temperature dependence coefficient change from 1970 to 2007

Month	Coefficient change (Pct/degr)/yr	R^2	Level of Sign.	Month	Coefficient change (Pct/degr)/yr	R^2	Level of Sign.
Jan	-3.24×10^{-3}	0.036	0.283	July	9.35×10^{-3}	0.031	0.317
Feb	-3.49×10^{-3}	0.018	0.444	Aug	16.7×10^{-3}	0.050	0.202
Mar	7.14×10^{-3}	0.110	0.051	Sep	21.9×10^{-3}	0.477	0.000
Apr	7.42×10^{-3}	0.096	0.070	Oct	16.8×10^{-3}	0.388	0.000
May	31.3×10^{-3}	0.724	0.000	Nov	-3.47×10^{-3}	0.044	0.236
Jun	34.4×10^{-3}	0.772	0.000	Dec	-3.74×10^{-3}	0.042	0.245

Table 6.1 shows the statistics of the regression of the time series for all months. Notice that the coefficient changes for May and June are the largest, whereas the changes in September and October are more modest. Although the correlation in other months is relatively minor and not found to be significant at $p<0.05$, it is noteworthy that all months from March to October show an increasing coefficient (positive coefficient change), whereas November to February show a decreasing coefficient (negative coefficient change).

6.5. Discussion

In this study we find significant changes in temperature dependence in May, June, September and October. Our results indicate a positive and increasing temperature dependence in the warmer months of the year. This finding is consistent with our hypothesis that increasing use of cooling applications would lead to an increasingly positive relation between temperature and electricity demand, especially during the summer months. Several points of discussion regarding these findings and their significance should be addressed.

Firstly, although our results suggest an increasing temperature dependence for several months, the lack of a significant trend in the real summer months July and August is remarkable. In fact, if in any month, the effect of increased use of cooling applications and air conditioning would be expected to be visible in the warmest months first. This lack of a trend may be due to the fact that summer holidays distort the electricity demand pattern in these months.

As noted in the methodology section, we have chosen not to use data correction methods in our study, except for the exclusion of non-working days. The chosen approach may be expected to lead to a high degree of variance in the data in the summer months. On most days of the summer months, a certain but fluctuating percentage of the population is on holidays, which generally leads to lower electricity demand because of lower economic activity. However, excluding holidays is difficult in these months because the timing of summer holidays is staggered over the country and varies per year. Generically excluding holidays would leave little data included for these months. Since days with relatively high economic activity (on which a relatively large part of the population is working) may fall on relatively warm days one year and on relatively cool days another year, the variation in economic activity may obscure any temperature dependence trend over the years. Thus, the effect of fluctuating economic activity on electricity demand in July and August may be expected to be larger than the effect of fluctuating temperature. Consequently, although the temperature dependence trend is found to be positive for both July and August, the variance of the deviation of this trend is too high to prove statistically significant.

However, notwithstanding the staggered timing of holidays, the end of July and the beginning of August may generally be considered holidays throughout the country. Therefore the working days during this summer holiday period possibly can be treated as a set of days with a reasonably stable activity pattern, although markedly different from that in non-holiday-months. We have therefore re-analyzed the data in sets that cover the timeframe from July 16 to August 15. We have excluded weekends similarly as in the other datasets. The analysis of these datasets shows a significant trend of $25.0 * 10^{-3}$ Pct/degree/year ($p=0.009$, $R^2=0.194$) for the coefficient change over the investigated time period from 1970 to 2007. Thus, a significant trend is found after all in the holiday summer months. However, the low R^2 shows that outdoor temperature cannot explain much of the volatility in electricity demand in this period, which corresponds with the hypothesis of a highly variable economic activity described above.

Secondly, we may wonder why we find a significantly positive trend in October, but not in April, even though days are shorter in October and both months are generally considered to have similar weather. A closer look at the data reveals that the average temperature in

October during the studied period is 1.6 degree higher than in April (Figure 6.8), although the difference has decreased over the decades we investigated. Thus the perception of similar weather is not correct. The temperature difference may explain the difference in the observed trend, since a higher temperature would lead to higher cooling and lower heating activity in October. An anonymous reviewer suggested that behavioral differences in air conditioning use between the start and the end of the summer season could also contribute to the observed difference. Furthermore, although the October trend is found to be significant and the April trend is not, both trends' low R^2 (0.388 for October, 0.096 for April) indicate a low predictive power. This observation and the fact that the temperature dependence coefficients in both months are relatively small, indicates that the temperature dependence in both April and October is a relatively inconclusive predictor for electricity demand. A repetition of the analysis using maximum temperatures instead of average temperatures supports this statement. In this additional analysis we generally found slightly different values for coefficients, R^2 and level of significance for all months, although the general conclusions remain the same. In this analysis, the trend for April and March becomes significant, although both still have a very low R^2, thus indicating that little difference in fact exists between April and October. Although this analysis generates these two additional significant results, we chose to describe our results based on average temperatures, because most relevant literature is based on average temperature. The additional significant results for March and April were judged to be of lesser importance than following the existing literature.

Thirdly, the value of the dependence coefficient found in this study suggests a current electricity demand variation of 0.5% of total demand per degree temperature change in May, June, September and the summer holidays. Since the value of this coefficient is defined by the observed variation and the absolute monthly electricity demand, the weight of this percentage depends on the absolute value of total Dutch electricity demand. Since total Dutch electricity demand is growing annually, a growing percentage signals a bigger share of a bigger pie. However, because of this dependence on total demand, some remarks on the developments in electricity generation should be kept in mind. The electricity load measurements used in this study are not synonymous to the total Dutch electricity demand. Increasingly, part of the demand is met by decentralized power generation, such as combined heat and power. Therefore the timing of operation of these decentralized systems influences the implications of our results. Decentralized systems that are operated on the basis of electricity prices, may have a dimming effect on the results from our study. After all, when electricity demand rises due to temperature increase, electricity prices go up. This price hike would lead to more decentralized systems being operated, which decreases the need for centralized production which is measured in our data. However, if decentralized systems are operated continuously, to reduce the price per kWh (as suggested by Boonekamp and Van Hilten [1990] before the liberalization of the electricity market), our findings may slightly overestimate the actual effect on total demand. Unfortunately, we do not have enough insight in decentralized electricity production data to conclusively assess its impact on our results.

Fourthly, given the (relatively small) 4-5% estimated share of cooling applications in the total electricity demand throughout the year, the finding of a 0.5%/degree temperature dependence on total electricity demand suggests a large temperature dependence of cooling demand itself. However, the 0.5% degree is still relatively small compared to the

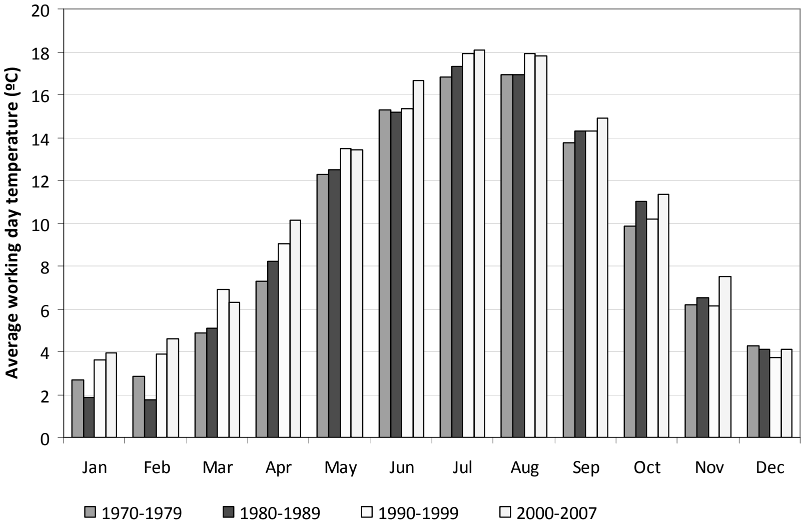

Figure 6.8 Average daily temperature on the working days included in the study, divided per decade. ***Adapted from [KNMI, 2008]***

temperature dependence observed in summer months in Spain, which we estimate in the order of 1.5-2%/degree based on Spanish data [Pardo et al., 2002].

Fifthly, although the hypothesis of increasing use of cooling application would explain our findings, there is also an alternative explanation of our findings. As mentioned before, the relation between electricity demand and temperature is usually found to be 'u' shaped [Mirasgedis et al., 2007; Moral-Carcedo and Vicéns-Otero, 2005; Nobel, 1996; Pardo et al., 2002; Valor et al., 2001]. This means that increasing average temperatures, would also lead to an increasing coefficient of temperature dependence in a certain month (see Figure 6.9). Figure 6.8 shows that indeed, average monthly temperatures in the last two decades were higher than in the first two decades under investigation. However, regression analysis between observed average monthly temperature and observed temperature dependence shows very low explanatory power (R2 between 0.00 and 0.279). Even so, higher temperatures, especially uncomfortably high temperatures, may be a driver for the purchase of air conditioning and other cooling applications [Sailor and Pavlova, 2003]. In this regard, higher temperatures may drive a socio-economic trend which may have a long lasting effect on future electricity demand. Thus, although the increasing average monthly temperature may partly explain the observed findings, it cannot account for all the observed development on its own. Furthermore, average October temperatures in the last decade (11.4 C) are still much lower than average June temperatures in the 1970s (15.3 C), but the observed temperature dependence coefficient is currently larger in October than in June in the 1970s. Therefore, the observed trend in temperature dependence requires an alternative explanation.

Lastly the dependence of total electricity demand on temperature results from the total underlying socio-economic structure. Therefore, a decrease in the importance of negatively temperature dependent processes, for instance a decreased importance of heating due to better insulation or higher heating efficiency, may lead to an increasingly positive temperature dependence just as an increase of positively temperature

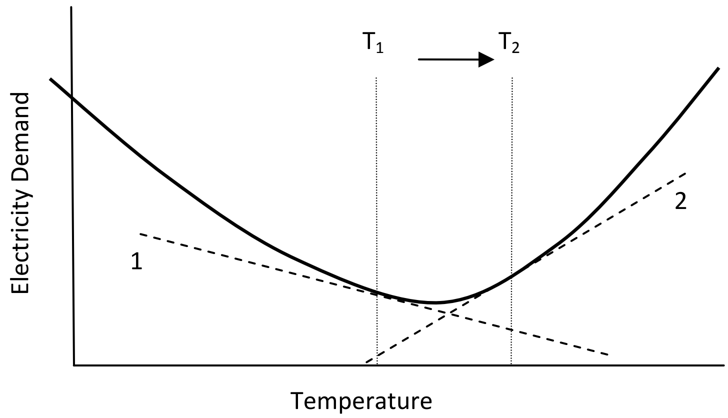

Figure 6.9 The effect of a changing average monthly temperature on temperature dependence. Since we define temperature dependence as the relation between electricity demand and temperature, temperature dependence at any temperature is represented in this graph by the tangent of the 'u' curve at that temperature. If average monthly temperature changes from T_1 to T_2, temperature dependence is thus expected to change from 1 to 2.

dependent processes would do. However, the electricity demand for heating in the Netherlands is limited mainly to the operation of electrical pumps, because Dutch heating systems are generally based on natural gas. Moreover, if changes in heating demand would be responsible for the increases in temperature dependence, we should find these changes mainly in winter instead of in summer months.

6.6. Implications of a changing temperature dependence

Given the dominance of winter electricity demand in Dutch electricity pattern, an increasing temperature dependence in summer months may not be thought to lead to general capacity issues in the Netherlands. However, the 2003 'code red' situation for Dutch electricity supply has shown that high summer temperatures in combination with extreme drought may lead to capacity problems [ECN, 2004]. Because cooling water availability was limited due to low water levels in rivers, and because surface water temperature limited the amount of cooling water allowed to be dumped, reserve capacity in the Netherlands dropped below 700MW, which resulted in extreme price spikes. An increasing temperature dependence may lead to such situations to occur more frequently. The expected temperature increase due to global warming may add to this increased frequency.

Apart from the effect of global warming on peak demand, it may also have effects on the future monthly electricity pattern. Since the temperature dependence coefficients for May, June, September, October and the summer holidays have become positive, it may be expected that a temperature increase due to global warming will lead to higher electricity demand in these months, thus possibly resulting in a (small) summer peak. Historically, the period of summer minimum was used as the main time to service and revise electricity plants in the Netherlands [Dijk and Geerts, 1988]. Since the liberalization of the electricity market however, maintenance planning should be regarded at a larger geographical scale, as expected demand and available production capacity in the whole of Western Europe sets the price for electricity, which may be expected to ultimately drive decisions to schedule servicing and maintenance. Nonetheless, since similar developments may occur in the rest of Europe, increasing summer demand may lead to plant servicing in spring and autumn, when prices are less volatile.

Moreover, additional capacity may be required to meet the additional summer demand. It has not escaped our attention that cooling demand in summer runs parallel with solar radiation and thus the capacity for solar electricity generation. Since conventional power stations have the temperature related capacity issues described above, sometimes leading to price spikes, this renewable electricity source may be a suitable alternative to meet the summer cooling demand.

Furthermore, our findings may also have consequences for the expected effects of global warming on future energy demand. The increasing temperature dependence found in this study may shift the balance between decreasing energy demand for heating purposes and increasing energy demand for cooling purposes as a result of global warming. Most studies investigating this relation assume a fixed balance temperature [Amato et al., 2005; Crowley and Joutz, 2005; Hadley et al., 2006; Ruth and Lin, 2006; Sailor, 2001; Sailor and Muñoz, 1997], mostly at 18ºC. The observed shift from negative to positive temperature dependence in this study in months with average temperatures below this temperature, suggests that this balance point may instead be variable in time. The assumptions on temperature dependence in these studies investigating this balance therefore need to be critically evaluated.

Lastly, many European countries have higher average summer temperatures than the Netherlands. The developments in the temperature dependence of electricity demand that we found for the Netherlands may be illustrative for other countries, in Europe and elsewhere. Interactions in the increasingly internationally oriented electricity market make that these findings should also be regarded at a pan-European level.

6.7. Conclusion

In this study we have investigated the electricity demand pattern in the relatively temperate climate of the Netherlands for possible changes related to the increased use of cooling applications. We have found significant increases in temperature dependence of electricity demand in May, June, September, October and during the summer holidays during the period 1970 – 2007. This trend has resulted in an increasingly positive temperature dependence during summer months, currently estimated around 0.5% of total electricity demand per degree temperature difference. If this trend continues, it may result in a summer electricity demand peak in the Netherlands, as seen in southern European countries, which may have important consequences for electricity generation capacity, maintenance scheduling and electricity prices. This development may also alter the expected effects of global warming on electricity demand, possibly shifting the balance between decreasing electricity demand for heating and increasing electricity demand for cooling resulting from global warming.

7. DYNAMIC TEMPERATURE DEPENDENCE PATTERNS IN FUTURE ENERGY DEMAND MODELS IN THE CONTEXT OF CLIMATE CHANGE[1]

Abstract *Energy demand depends on outdoor temperature in a 'u' shaped fashion. Various studies have used this temperature dependence to investigate the effects of climate change on energy demand. Such studies contain implicit or explicit assumptions to describe expected socio-economic changes that may affect future energy demand.*

This chapter critically analyzes these implicit or explicit assumptions and their possible effect on the studies' outcomes. First we analyze the interaction between the socio-economic structure and the temperature dependence pattern (TDP) of energy demand. We find that socio-economic changes may alter the TDP in various ways. Next we investigate how current studies manage these dynamics in socio-economic structure. We find that many studies systematically misrepresent the possible effect of socio-economic changes on the TDP of energy demand. Finally, we assess the consequences of these misrepresentations in an energy demand model based on temperature dependence and climate scenarios. Our model results indicate that expected socio-economic dynamics generally lead to an underestimation of future energy demand in models that misrepresent such dynamics. We conclude that future energy demand models should improve the incorporation of socio-economic dynamics. We propose dynamically modeling several key parameters and using direct meteorological data instead of degree days.

7.1. Introduction

The possible effect of climate change on energy demand has recently renewed the interest in the relation between energy demand and outdoor temperature [Aebischer et al., 2007; Amato et al., 2005; Cartalis et al., 2001; Hadley et al., 2006; Isaac and Van Vuuren, 2009; Sailor and Pavlova, 2003; Wilbanks et al., 2007]. Various empirical studies have found total energy demand [Amato et al., 2005], combined natural gas and electricity demand [Sailor and Muñoz, 1997] and electricity demand [Bessec and Fouquau, 2008; Franco and Sanstad, 2008; Mirasgedis et al., 2007; Moral-Carcedo and

[1] This chapter is a slightly adapted version of Hekkenberg, Moll and Schoot Uiterkamp (2009). *Dynamic temperature dependence patterns in future energy demand models in the context of climate change.* Energy (*in press*). doi:10.1016/j.energy.2009.07.037

Vicéns-Otero, 2005; Valor et al., 2001] to depend on outdoor temperature in a u-shaped fashion; low temperatures correspond to relatively high energy demand, intermediate temperatures correspond to lower energy demand, and high temperatures correspond to higher energy demand again. Such a "temperature dependence pattern" (TDP) [2] may be explained by a higher energy demand for heating processes at low temperatures and a higher energy demand for cooling processes at high temperatures.

A u-shaped TDP suggests that climate change may have ambiguous consequences for future energy demand. Increasing outdoor temperatures could generally reduce heating demand, but could also increase cooling demand. Given spatial and seasonal variations in the relative importance of these opposing effects, the sign of the overall balance for energy demand may thus vary regionally and seasonally. Obviously, assessing future energy demand is important for the purpose of future energy supply planning and economic assessments. Moreover, given that the current energy systems are at the base of greenhouse gas emissions, demand variation resulting from climate change may have implications for future greenhouse gas emission reduction requirements and abatement options both regionally and globally. Therefore, future energy demand projections may be improved by including the energy demand effects of climate change.

The approach to project regional or global energy demand implicitly assumed above, requires an expected TDP to describe energy demand at given temperatures and an expected climate pattern to describe the projected frequency distribution of given temperatures throughout the year. The sum of products of TDP and climate pattern results in the projected annual energy demand. Comparison of the projected energy demand resulting from a given TDP in various climate scenarios can clarify the effect of climate change on energy demand. The required climate patterns can be taken from climate models, but can also be composed by simply adding a given number of degrees to the currently observed climate pattern. However, the estimation of the TDP depends on many underlying socio-economic parameters.

Total energy demand and the TDP are influenced by a wide array of structural indicators, such as the general degree of economic welfare, the extent of electrification, the availability of other energy carriers, the prevalence of energy efficient technologies, the prevailing climate and cultural habits [Aebischer et al., 2007; Amato et al., 2005; Hadley et al., 2006; Henley and Peirson, 1997]. There are large differences in the socio-economic structure underlying energy demand throughout the world both relative to the total energy demand and on an absolute scale. All these regional structural differences may naturally result in different regional TDPs. The TDP of a given region can thus be regarded as an indicator of the underlying socio-economic system.

However, the TDP may not only vary by location; structural socio-economic developments, such as increasing the capacity or energy-efficiency of heating or cooling applications, may also change a local TDP over time. Moral-Carcedo and Vicéns-Ocero [2005] have modeled the Spanish TDP for electricity in a rolling average of 3-yr periods, and show that it is subject to change. Bessec and Fouquau [2008] have suggested similar findings for the EU-15 and Hekkenberg et al. [2009] show the pattern in the Netherlands

[2] In this study, TDP is defined as the function of expected daily energy demand at a continuum of outdoor temperatures.

has also been changing. Accurately projecting a future TDP thus requires data on both current regional details and expected regional developments.

Many studies modeling the effect of climate change on energy demand to date focus solely on the effects of temperature change [Cartalis et al., 2001; Franco and Sanstad, 2008; Sailor, 2001; Thatcher, 2007], and thereby assume implicitly that the socio-economic structure does not change. Others use more explicit assumptions that do allow some socio-economic dynamics that may influence the studied effects [Amato et al., 2005; Hadley et al., 2006; Isaac and Van Vuuren, 2009; Mirasgedis et al., 2007; Sailor and Pavlova, 2003].

This chapter critically explores the implicit or explicit assumptions in studies investigating the effects of climate change on future energy demand. It analyzes the possible effects of socio-economic dynamics on the TDP (section 7.2) and investigates how current studies approach these dynamics (section 7.3 and 7.4). Next it models the consequences of misrepresenting such dynamics in studies that model the effect of climate change on future energy demand (section 7.5 and 7.6) and discusses possible implications (section 7.7). Finally, section 7.8 presents the conclusions of the study. Note that the study aims to improve the methodology of future energy demand forecasts, rather than forecast energy demand itself.

7.2. Socio-economic differences and developments in the temperature dependence pattern

In describing the effect of various socio-economic differences in the TDP, we can discriminate between continuous heating or cooling processes and comfort related heating or cooling processes. Continuous processes may be expected to operate regardless of the outdoor temperature, whereas comfort related processes may be expected to operate within a certain temperature range only.

Continuous heating demand may e.g. be expected in various industrial processes. Continuous cooling demand may e.g. be expected in food processing and storage, both industrially, commercially and domestically.

For industrial processes, heating and cooling demands are often considered to be independent of outdoor temperature [Amato et al., 2005], possibly because the temperature difference to bridge in such processes is often much larger than the outdoor temperature fluctuations. Also, many other continuous processes operate at relatively stable surrounding temperatures and thus have a relatively stable demand. However, e.g. continuous cooling processes related to food processing and storage have relatively small temperature differences to bridge, and thus possibly are more dependent

on outdoor temperature, especially since these cooling processes often exchange heat to the outdoor air. Therefore, part of the continuous demand may be expected to be temperature dependent. The combined positive, negative or neutral effect of these continuous processes depends on the relative contribution and temperature dependencies of continuous heating and cooling processes in the total energy demand. Socio-economic developments may increase or decrease the relative share of these continuous processes in total energy demand and thus possibly change their aggregated temperature dependence.

Comfort related heating and cooling demand may be expected in many places where people live or work. These processes are aimed at raising or lowering the ambient temperature in a living or working space within a certain human comfort zone. The temperature at which no heating or cooling is required to keep the indoor temperature at the required level is generally called the balance temperature [Cartalis et al., 2001].

Figure 7.1 shows a schematic representation of heating and cooling demands in indoor spaces conditioned towards a given human comfort level. Various developments are shown that may alter the need for heating or cooling at given temperatures [Aebischer et al., 2007]. From this representation we can see that increasing insulation, increasing heating efficiency, increasing internal heat gains (e.g. from more use of electric appliances) and a changing human comfort pattern (e.g. thicker clothing) may shift the need for heating towards lower temperatures. Obviously, shifts towards higher temperatures could also occur from opposite developments. Similarly, the need for cooling may be shifted by various structural changes. Noteworthy is that increasing internal heat gains lead to decreasing heating demand, but also to increasing cooling demand. Arguably, the sum of societal trends, such as better insulation, increased internal heat gains in (office) buildings from e.g. computers or a decreasing tolerance for heat, leads to a general shift towards lower heating demand and higher cooling demand [Aebischer et al., 2007]. Efficiency improvements and better insulation can reduce both heating and cooling demands and possibly further shift the temperature range in which such demand occurs.

Summarizing, various socio-economic factors may influence the total energy demand for heating and cooling related to space conditioning and may thus influence the TDP.

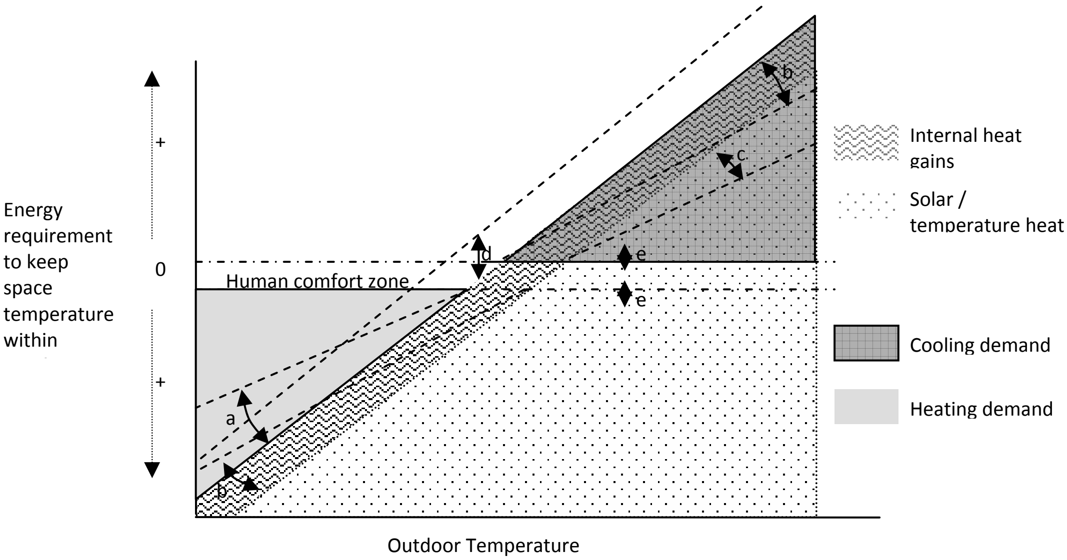

Figure 7.1 Schematic representation of energy requirement to maintain space temperature within a specified comfort zone and examples of shifting demand by various structural changes. a= increase in heating efficiency; b= improved insulation; c= improved cooling efficiency; d= increasing internal heat gains; e= changing human comfort patterns.

7.3. Current approaches to establish the temperature dependence pattern

Several current approaches to assess the effect of climate change on energy demand [Amato et al., 2005; Franco and Sanstad, 2008; Mirasgedis et al., 2007; Parkboom and Harrison G.P, 2008; Sailor and Pavlova, 2003; Sailor, 2001; Thatcher, 2007] conceptually build on and extend into the future the existing successful approaches to describe the effect of temperature variation on the intra-daily, daily or monthly electricity demand [Al-Zayer and Al-Ibrahim, 1996; Beccali et al., 2008; Bessec and Fouquau, 2008; Moral-Carcedo and Vicéns-Otero, 2005; Pardo et al., 2002; Valor et al., 2001] or energy demand [Amato et al., 2005; Sailor and Muñoz, 1997] by correlating historic demand variation with temperature variations. Others use models that simulate building characteristics in order to calculate energy demand at various temperatures bottom upwards [Cartalis et al., 2001; Rosenthal and Gruenspecht, 1995; Scott et al., 1994].

The best known approach to link energy demand with outdoor temperature is through the concept of degree days. Heating degree days (HDDs) and cooling degree days (CDDs) describe the departure of daily average temperature down or up from a threshold temperature (Tb). Clearly, these names suggest that degree days coincide with the requirement of heating or cooling at the given temperature. The summed totals of HDDs and CDDs over a given period therefore form indicators for cold and heat stress respectively, and form relatively simple metrics to describe a region's climate. Higher HDD and CDD totals have both been successfully correlated with higher electricity demand [Beccali et al., 2008; Le Comte and Warren, 1981; Valor et al., 2001] or natural gas consumption [Amato et al., 2005; Sailor and Muñoz, 1997]. Mathematically, the degree day model may be represented through equation (1).

$$ED = d * EDTb + \alpha * (HDD) + \beta * (CDD) \tag{1}$$

In which
ED = total energy demand over a given period,
EDTb = Base daily energy demand (at T=Tb),
d = number of days in given period,
HDD = summed daily temperature deviation down from Tb in given period,
CDD = summed daily temperature deviation up from Tb in given period,
α = regional dependence of ED on cold stress,
β = regional dependence of ED on heat stress.

Because degree days are basically a simple conversion of outdoor temperature, a TDP can be derived from equation (1) by calculating expected daily energy demand at a given daily temperature. The observed u-shaped relation between energy demand and temperature is thus simplified by two linear functions of temperature in a v-shape (e.g. in [Amato et al., 2005]). Approaches to assess energy demand generally presume these functions to represent heating demand and cooling demand. The slopes of these functions (given by α and β in equation (1)) determine the TDP of energy demand (see Figure 7.2).

Hence we can describe heating and cooling demands in such a TDP as follows:

HD = α(Tb-T) for (T< Tb) (2)

CD = β(T-Tb) for (T> Tb) (3)

In which
HD = Heating demand,
CD = Cooling demand,
α = regional dependence of ED on cold stress,
β = regional dependence of ED on heat stress,
T = daily average temperature,
Tb= threshold temperature between heating demand and cooling demand.

The TDP is completed by adding the temperature independent demand that exists at all temperatures.

As discussed in section 7.2, temporal dynamics may influence the slopes of the pattern as well as the threshold temperature for heating and cooling demands. Allowing for variation in the slopes of the functions for heating and cooling demands and a regionally variable threshold temperature in the TDP are needed to allow for spatial and temporal socio-economic dynamics in future energy demand projections.

However, the regression based TDPs are principally static, because α and β are derived by regression of aggregated data. Still, α and β could be adjusted to enable incorporating some of the socio-economic dynamics, although the exact influence of dynamics on these parameters remains unclear because the regression provides no explanatory mechanisms. Bottom up approaches [Cartalis et al., 2001; Rosenthal and Gruenspecht, 1995; Scott et al., 1994] are therefore generally better suited to incorporate dynamics.

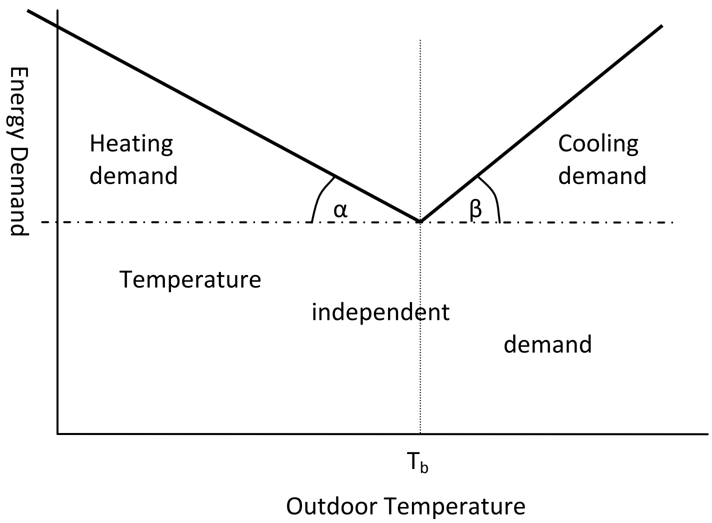

Figure 7.2 TDP based on a degree day approach.

7.4. Current approaches to incorporate dynamics in the temperature dependence pattern

This section discusses how various studies have dealt with spatial and temporal variations and point out several observed misrepresentations of these variations. Various studies deal with a single region only [Amato et al., 2005; Cartalis et al., 2001; Franco and Sanstad, 2008; Mirasgedis et al., 2007] and can therefore neglect the issue of regional structural differences. They establish the regional TDP from electricity or energy data for each region. Studies that cover multiple regions, generally establish the TDP separately for each region being investigated [Isaac and Van Vuuren, 2009; Sailor and Muñoz, 1997].

Many studies neglect structural changes during the investigated period. Such studies implicitly assume that the observed regional TDP, or some of its key elements, is static. For investigating short-term energy or electricity demand variation this would be justified, since manifestation of structural changes is negligible on a day to day basis. However, studies that use the TDP for assessments of the effects of climate change on future energy demand clearly have a long-term scope. Although these studies usually include obvious economic parameters such as Gross National Product (GNP) and population growth rates, they often neglect possible structural changes that may change the relative TDP [Cartalis et al., 2001; Franco and Sanstad, 2008; Hadley et al., 2006; Mirasgedis et al., 2007; Rosenthal and Gruenspecht, 1995]. Therefore, structural changes in the relative importance of heating or cooling processes in regional economies are not accounted for, even though these may be significant in long-term forecasting.

Still, other studies do include various structural changes in their energy demand forecast. For instance, Sailor and Pavlova [2003] estimate regional energy demand for space conditioning based on future societal penetration of air conditioning applications. Isaac and Van Vuuren [2009] additionally include energy efficiency development and projected future income in a global assessment of residential sector energy demand for heating and air conditioning. Belzer et al. [1996] and Scott at al. [1994] model changes in space conditioning system and building characteristics. In terms of the TDP, these approaches dynamically model the slope parameters (α and β) of the pattern, which is crucial for including the dynamics of structural developments. Thus, these studies address some of the major deficits found in other studies. However, many studies use the degree days concept to establish the TDP. We argue that this concept has fundamental shortcomings, which may lead to a misrepresentation of future TDP.

The observed correlation between degree days and energy demand is usually logically linked to energy demand for heating and cooling processes. The comparison of the degrees days based TDP in Figure 7.2 and the graphical bottom up representation of heating and cooling demands in Figure 7.1 shows remarkable similarities. However, we argue that the fundaments leading to the graphs should not be matched without due consideration. After all, other societal processes could possibly similarly explain (part of) the observed correlation. For instance, electricity use for lighting is also generally correlated to temperature, since winter months are usually colder but also darker. If such processes are falsely included as heating demand, a decrease in heating demand due to climate change may be overestimated, since lighting demand may be expected not to be influenced by climate change. In essence the degree days approach is a regression approach, which can serve as an underpinning of but not as the base for logical explanation. Moreover, the usual approach to aggregate data from long time series to establish correlations inhibits the revelation of possible historic dynamics. Using a similar approach to forecast future demand similarly neglects possible future dynamics.

The degree days concept generally presumes a static threshold temperature of 18ºC (65F) by default. As can be deducted from Figure 7.1, this threshold temperature is not necessarily equal for heating and cooling demands. Moreover, threshold temperatures for heating and cooling may vary individually, due to socio-economic developments or behavioral changes. Various studies report that a different threshold temperature would better represent the observed data in a given region [Amato et al., 2005; Sailor and Muñoz, 1997], however some use the default threshold temperature to be in line with other studies and thus disregard the possibly existing regional differences [Isaac and Van Vuuren, 2009]. Some [Amato et al., 2005; Cartalis et al., 2001; Rosenthal and Gruenspecht, 1995] use separate threshold temperatures to model heating and cooling demands, but do not assume any dynamics in these temperatures. Others do model a slightly changing threshold temperature [Belzer et al., 1996] or include the choice of threshold temperature in their sensitivity analysis [Rosenthal and Gruenspecht, 1995].

Moreover, the degree days approach assumes that heating demand and cooling demand never co-exist. Although this may seem plausible for space conditioning (as represented in Figure 7.1), it disregards the share of demand that serves other purposes, such as food conservation or industrial heating and cooling processes, which we discussed in section 2[3]. We suggest that degree day correlation should be explained as the result of *interaction* between heating and cooling demand (and other societal processes), rather than as the manifestation of just either one of them. In this interpretation, the observed slope of the TDP reflects the difference between the change in heating demand and the

Table 7.1 Possible misrepresented parameters of the TDP from misrepresented dynamics.

		Main effect on TDP	
		Slope	Threshold temperature
Observed shortcomings in study methodologies	Misrepresentation of regional differences		X
	Misrepresentation of temporal dynamics	X	X
Errors resulting from degree day approach characteristics	Falsely including or excluding processes in heating or cooling demand estimate	X	
	Interaction between socio-economic developments		X
	Interaction between heating and cooling demand	X	X

[3] E.g. In the Netherlands cooling demand for air conditioning, refrigeration and freezing processes is collectively estimated at 4-5% of total national electricity demand (KWA, 2005), even though average daily temperatures rarely rise above 18C. At the usual threshold temperature of 18ºC, a degree days approach cannot estimate such demand.

change in cooling demand resulting from temperature variation. Since the slopes of heating and cooling demands have opposite signs, the individual slopes of heating and cooling demand separately may be larger than the observed combined slope. Therefore, socio-economic developments that affect heating or cooling demand may be underestimated if the combined slope is treated as the individual heating or cooling slope. Moreover, because of such interaction between various types of demand, socio-economic developments may result in a shifting of the temperature with minimum energy demand.

Summarizing, studies assessing the effects of climate change on energy demand do not always accurately represent spatial differences and temporal dynamics leading to TDP variation. The misrepresentation of the present or future TDP may lead to errors in the energy demand forecasts. Misrepresenting spatial differences may lead to erroneous baselines on which to base the projections, whereas misrepresenting temporal developments may lead to erroneous projections. Consequently, misrepresentations may lead to errors in the resulting assessment of the effects of climate change on energy demand. Table 7.1 summarizes the discussed misrepresentations and the TDP parameters that they may influence.

7.5. A linear model to analyze structural dynamics in climate change scenarios

We have developed a linear Microsoft Excel model to analyze the consequences of the shortcomings discussed in the previous section. Equation 4 formally describes the model's energy demand calculation.

$$
\begin{aligned}
ED &= \sum_{i=1}^{n} (TID + \alpha\sigma_H (T_{bH} - T_i) + \beta\sigma_C (T_i - T_{bC}) + \gamma T_i) \\
\sigma_H &= \begin{cases} 0, & T_{bH} - T_i < 0 \\ 1, & T_{bH} - T_i \geq 0 \end{cases} \\
\sigma_C &= \begin{cases} 0, & T_i - T_{bC} < 0 \\ 1, & T_i - T_{bC} \geq 0 \end{cases}
\end{aligned}
\tag{4}
$$

In which

ED	= annual energy demand,
n	= number of days in a year,
TID	= daily temperature independent demand,
α	= temperature dependence of heating demand,
β	= temperature dependence of cooling demand,
γ	= temperature dependence of continuous temperature dependent demand,
Ti	= average temperature on day I,
TbH	= upper threshold temperature for heating demand,
TbC	= lower threshold temperature for cooling demand,
σH and σC	= step function parameters that indicate the existence of heating demand and cooling demand.

The annual set of daily average temperatures is generated from the climate pattern sub-model described below. The other model parameters can be set, which allows to build a TDP bottom upwards, e.g. to simulate a V-shaped TDP similar to a degree days based pattern. Changing the model parameters results in TDPs with different temperature dependences (α, β) or threshold temperatures (TbH and TbC) of heating and cooling demand, which can be used to simulate different socio-economic systems. To simulate degree days based approaches TbH should equal TbC (usually at 18ºC). Additionally, the parameter γ is included to represent the temperature dependence of continuous temperature dependent demand. Figure 7.3 graphically presents the four different types of energy demand that constitute the TDP: heating demand, cooling demand, continuous temperature dependent demand and continuous temperature independent demand. Figure 7.3 also presents the effect of various parameter changes on the TDP. Note that in the graphic γ is cumulative to α and β.

The presented approach principally allows to model all independent parameters dynamically, in order to represent socio-ecomomic changes over time. However, in this chapter we compare the results from different static TDPs to provide insight in the effects of various socio-economic dynamics. We assess several scenarios, which all compare four different TDPs that result from varying one or various model parameters. For each TDP and climate pattern the percentage change in total annual energy demand due to climate change is calculated by comparing ED in 'current climate' and in 'current climate +2ºC'. Each single model run in fact simulates a static socio-economic system, since it does not change the TDP; the change in projected energy demand results purely from the different climate patterns. Comparing the scenario runs with differing TDPs allows to test the consequences of several of the deficits indicated before. Specifically, we test six scenarios (listed in Table 7.2) that may occur through socio-economic dynamics but may not be represented correctly through the degree day based approaches. The numbers in Figure 7.3 correspond to these different scenarios. The parameters' settings used in the six scenarios are reported in Table 7.3. Note that the chapter describes relative energy demand differences rather than absolute energy demand. Any volume changes occurring from growth in GNP, population, etc., should be included in the parameter dynamics when estimating future absolute energy demand.

In order to more easily understand the results, the parameters are fitted in such a way that average daily energy demand before climate change is standardized at 100 units (u) in each combination of TDP and climate pattern. Note however, that this approach implies a different continuous temperature independent demand in each climate pattern, because the shares of heating and cooling demands compared to total demand depend on the assumed climate pattern. Consequently, the TDPs differ for each climate pattern, although they have equal slopes and threshold temperatures. This restrains comparison across climate patterns. However, given that the TDPs represent socio-economic systems, and that generally, socio-economic systems differ across climate zones, such a comparison would be purely theoretical rather than practically valuable anyway.

The model parameters obviously need to be chosen in such a way that total heating and cooling demands form a realistic part of total energy demand. A value of 1 u/ºC for α means that each degree Celsius below T_{bH} results in an increase of heating demand by 1% of the average daily energy demand. A value of 1 u/ºC for β means that each degree Celsius above T_{bC} results in an increase of cooling demand by 1% of the average daily energy demand. The value for γ can be positive or negative, implying that each degree temperature change results in an increase or decrease of continuous temperature dependent demand respectively. In the TDPs simulating degree days based approaches γ is set at 0 u/ºC. The absolute level of continuous temperature dependent demand has no impact on the results and is therefore set at 0 u at 0 ºC in all scenarios, even though this may lead to negative values for continuous temperature dependent demand. Finally, the level of continuous temperature independent demand (TID) is selected in such a way that the average daily energy demand before climate change equals the standard value of 100 u in each combination of TDP and climate pattern.

Table 7.2 List of the tested scenarios.

▪ **A changing temperature dependence of cooling demand**
▪ A changing temperature dependence of heating demand
▪ A changing threshold temperature that separates heating and cooling demand
▪ A combination of changing dependencies of heating and cooling demand and a changing threshold temperature
▪ A changing continuous temperature dependent demand
▪ A changing threshold temperature for heating or cooling demand individually

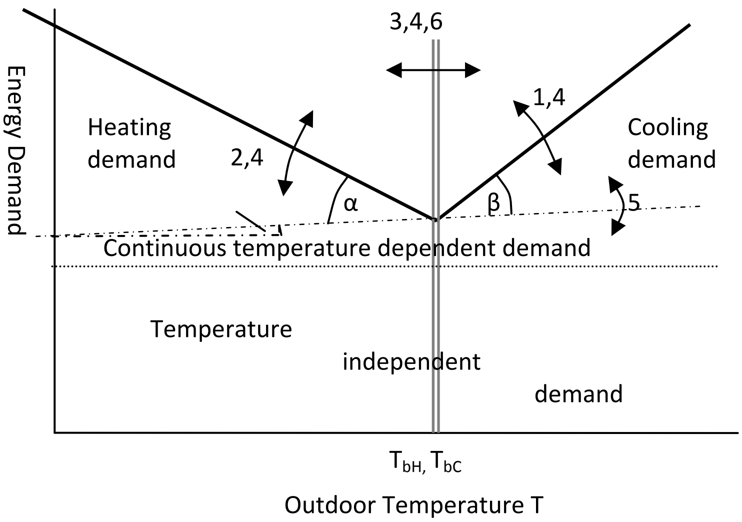

Figure 7.3 The effect of various parameter changes on the TDP given in figure 2. Arrows and numbers correspond to the parameter changes modeled in scenarios 1-6.

Table 7.3 Parameter settings in scenarios 1-6.

	Pattern	T_{bH} (ºC)	T_{bC}(ºC)	α (u/ºC)	β (u/ºC)	γ (u/ºC)
Scenario 1	A	18	18	1.5	1	0
	B	18	18	1.5	1.5	0
	C	18	18	1.5	2	0
	D	18	18	1.5	3	0
Scenario 2	A	18	18	2	1.5	0
	B	18	18	1.5	1.5	0
	C	18	18	1	1.5	0
	D	18	18	0.5	1.5	0
Scenario 3	A	20	20	1.5	1.5	0
	B	18	18	1.5	1.5	0
	C	16	16	1.5	1.5	0
	D	14	14	1.5	1.5	0
Scenario 4	A	20	20	2	1	0
	B	18	18	1.5	1.5	0
	C	16	16	1	2	0
	D	14	14	0.5	3	0
Scenario 5	A	18	18	1.5	1.5	-0.6
	B	18	18	1.5	1.5	-0.3
	C	18	18	1.5	1.5	0.3
	D	18	18	1.5	1.5	0.6
Scenario 6	A	18	18	1.5	1.5	0
	B	16	18	1.5	1.5	0
	C	14	18	1.5	1.5	0
	D	12	18	1.5	1.5	0

Table 7.4 Average temperatures and corresponding standard deviations selected as climate patterns.

	Selected climate patterns									
Average temperature (ºC)	8	10	12	14	16	18	20	22	24	26
Standard deviation (ºC)	6.25	6	5.75	5.5	5.25	5	4.75	4.5	4.25	4

Climate pattern sub-model

Equation 4 theoretically allows to use sets of observed daily temperatures in various climate zones. However, to facilitate comparison, the climate patterns used in the chapter are created by assuming a normal frequency distribution around a specified yearly average temperature ranging from 8 to 26 ºC, even though we acknowledge that actual temperature frequency distributions are not perfect normal distributions. We assume that the standard deviation becomes smaller at higher average temperatures (from 6.25 to 4 ºC) to reflect the generally smaller temperature deviation in warmer climates [McKittrick et al., 1991]. The average temperatures and respective standard deviation of the selected climate patterns are shown in Table 7.4. We assume that the standard deviations remain equal when average temperatures increases by 2 ºC due to climate change.

7.6. Model results

The results from the six tested scenarios are presented in Figure 7.4 through Figure 7.9. Each figure shows the results of a simulation of 4 different TDPs (patterns A-D) for 10 different climate scenarios. The depicted bars represent the relative difference in energy demand resulting from a 2 ºC temperature increase for each combination of TDP and climate scenario.

The differences resulting from using different TDPs show that the effects of climate change depend on the assumed TDP. Because we use hypothetical parameter values as input in our model, the changes in energy demand from individual model runs are not very relevant; choosing different values leads to different outcomes. When evaluating the results, we should therefore look at the relative changes between model runs rather than the absolute numbers of the model runs themselves.

As explained in section 7.5, the results for different climate patterns are based on different TDPs, albeit with equal slopes and threshold temperatures. Therefore, the resulting values can not be compared across the climate patterns. However, comparing the direction of changes across the climate patterns can indicate the significance of the effects from socio-economic changes on a globally aggregated scale.

7.6.1. Scenario 1 – A changing cooling dependence

In this scenario (Figure 7.4), patterns A-D reflect TDPs in which the temperature dependence of cooling demand increases from pattern A to D, while keeping other temperature dependent parameters equal.

The results show that an increased cooling dependence leads to a smaller decrease or a larger increase of energy demand in temperature scenarios that result in a decrease or increase of energy demand respectively. Underestimating the temperature dependence of cooling demand (by assuming a too low value for β) apparently leads to underestimation of the total energy demand in climate change scenarios. Overestimating the temperature dependence obviously leads to overestimating the demand. This effect is projected under all climate conditions, but is the largest in warmer climates. Under some climate conditions the increasing temperature dependence of cooling demand results in an increase in energy demand rather than a decrease. Apparently, an increasing temperature dependence of cooling demand results in a shift of the “balance climate” towards a lower average temperature. The balance climate is the climate pattern at which increasing cooling demand due to climate change exactly compensates the decreasing heating demand. In colder climates climate change results in lower total energy demand and in warmer climates the opposite occurs.

7.6.2. Scenario 2 – A changing heating dependence

In this scenario (Figure 7.5), pattern A-D reflect TDPs in which the temperature dependence of heating demand decreases from pattern A to D, while keeping other temperature dependent parameters equal. The effects of a decreasing temperature dependence of heating demand are essentially similar to those of an increasing temperature dependence of cooling demand, except that in this scenario, colder climates show a larger effect than warmer climates. Underestimating the temperature dependence of heating demand thus leads to overestimation of energy demand, whereas overestimating the temperature dependence of heating demand leads to underestimation of energy demand. A decreasing temperature dependence of heating demand results in a shift of the balance climate towards lower average temperature.

7.6.3. Scenario 3 – A changing threshold temperature that separates heating and cooling demand

In this scenario (Figure 7.6), patterns A-D reflect TDPs in which the threshold temperature shifts towards lower temperatures from pattern A to D, while keeping other temperature dependent parameters equal.

The results show that a lower threshold temperature leads, again, to a smaller decrease or a larger increase of energy demand in temperature scenarios that result in a decrease or increase of energy demand respectively. The largest differences are observed in climate patterns around T_b. Neglecting a downwards shifting threshold temperature leads to an underestimation of energy demand resulting from a temperature increase. As may be expected, a lower T_b results in a shift of the balance climate towards lower average temperature.

7.6.4. Scenario 4 – A combination of changing the dependencies of heating and cooling demands and a changing threshold temperature

In this scenario (Figure 7.7), patterns A-D reflect a combination of the previous TDPs. The results shows large differences between the patterns, in the same general direction as described in the earlier 3 scenarios. This scenario is designed to show that the simultaneous occurrence of several developments may augment the effects. The combination of parameters is therefore chosen in such a way that their effects on the results are all augmenting. A different combination of developments would obviously lead to less drastic differences.

7.6.5. Scenario 5 – A changing continuous temperature dependent demand

In this scenario (Figure 7.8), patterns A-D reflect TDPs that include a continuous temperature dependent demand. The continuous temperature dependent demand is modeled to change from negative to positive from pattern A to D, while keeping other temperature dependent parameters equal. In fact the effect of this change is similar as the effect of simultaneously increasing cooling demand temperature dependence and decreasing heating demand temperature dependence. Therefore the results show similar trends as in previous scenarios. The negligence of changes in continuous temperature dependent demand may therefore lead to underestimation or overestimation of total demand, depending on the direction of change.

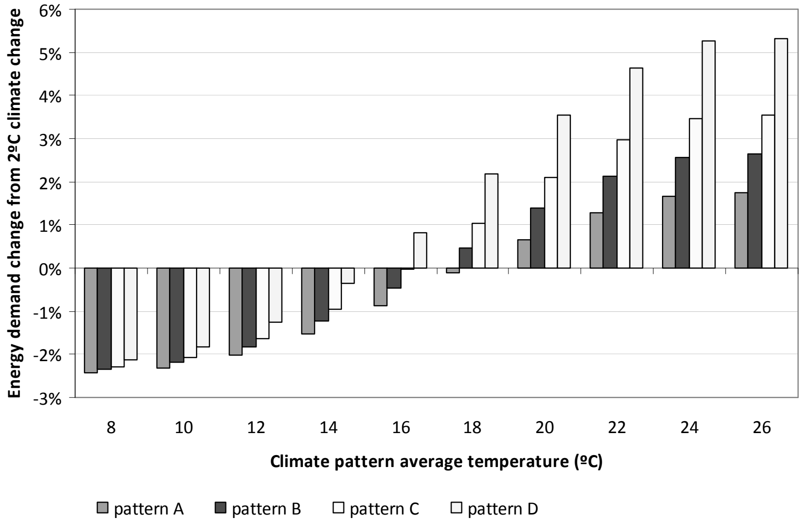

Figure 7.4 Effect of a changing cooling dependence (scenario 1). Patterns A-D represent TDPs in which the temperature dependence of cooling demand increases from pattern A to D.

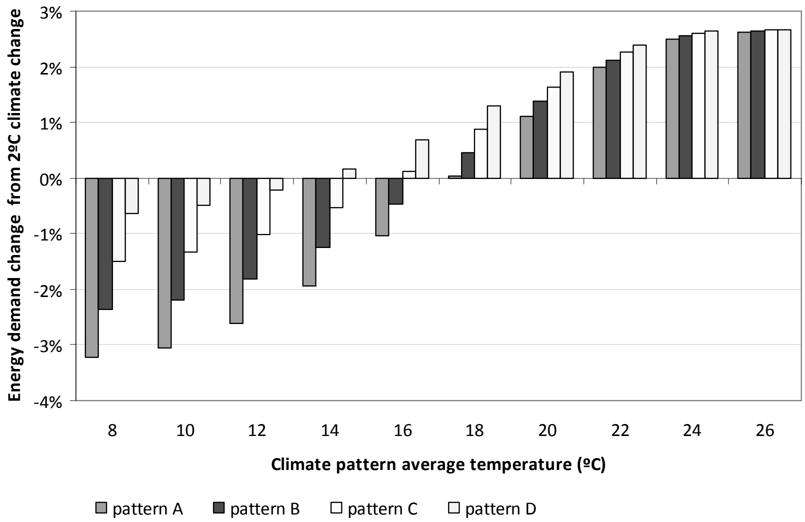

Figure 7.5 Effect of a changing heating dependence (scenario 2). Patterns A-D reflect TDPs in which the temperature dependence of heating demand decreases from pattern A to D.

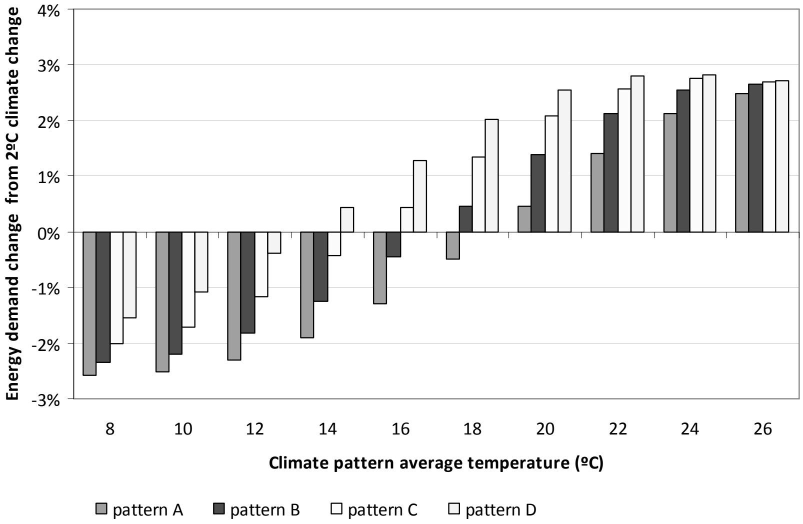

Figure 7.6 Effect of a changing threshold temperature (scenario 3). Patterns A-D reflect TDPs in which the threshold temperature shifts towards lower temperatures from pattern A to D.

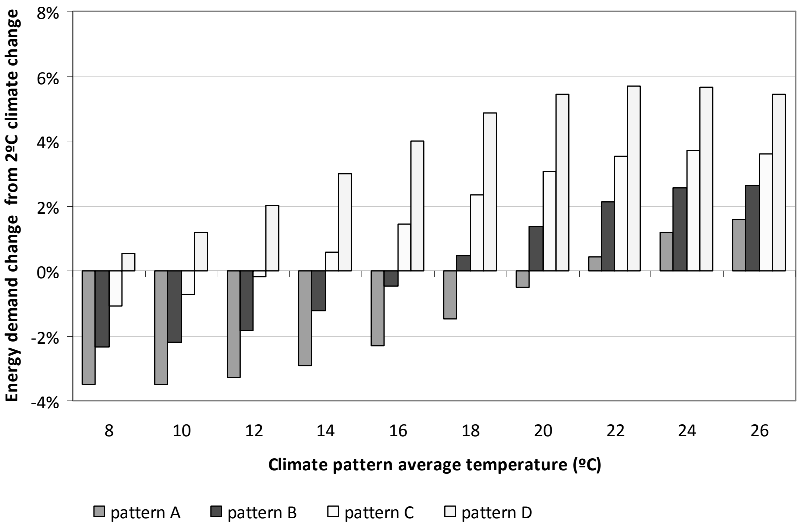

Figure 7.7 Effect of a combination of a changing heating and cooling dependence and a changing threshold temperature (scenario 4). Patterns A-D reflect a combination of the TDPs in scenarios 1 to 3.

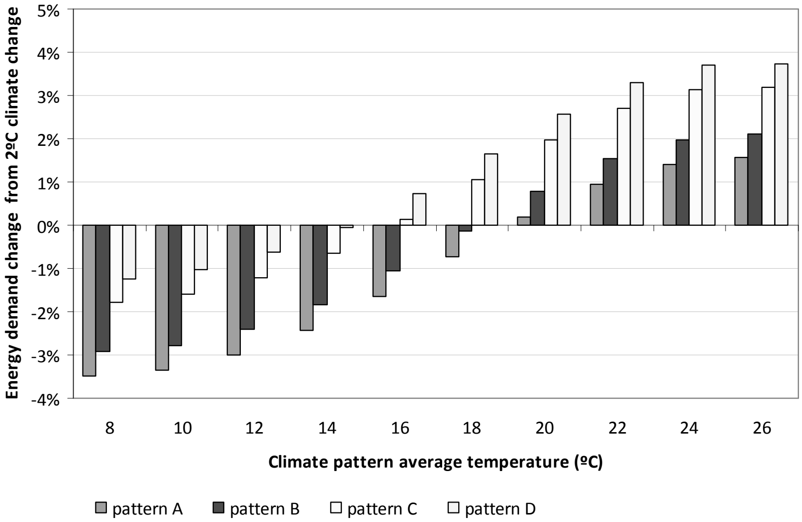

Figure 7.8 Effect of a changing continuous temperature dependent demand (scenario 5). Patterns A-D reflect TDPs that include a continuous temperature dependent demand which is modeled to change from negative to positive from pattern A to D.

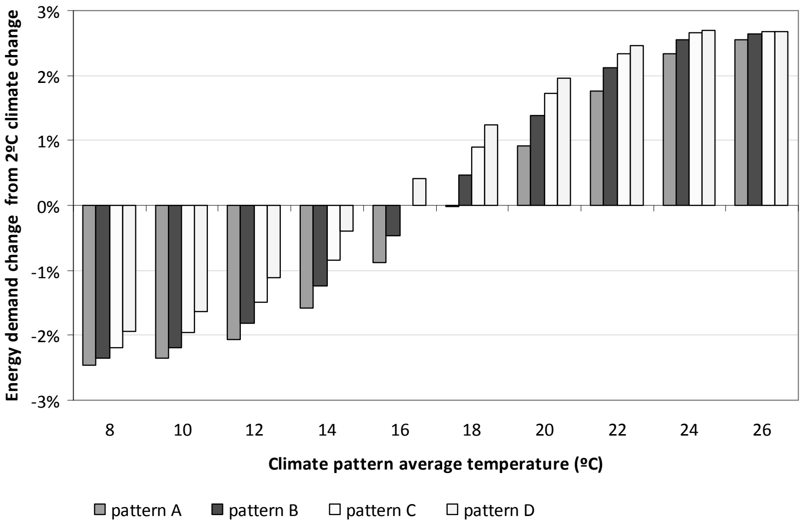

Figure 7.9 Effect of a changing threshold temperature for heating and cooling demand individually (scenario 6). Patterns A-D reflect TDPs in which the base temperature for heating demand shifts towards lower temperatures from pattern A to D.

7.6.6. Scenario 6 – Changing threshold temperature for heating or cooling demand individually

In this scenario (Figure 7.9, patterns A-D reflect TDPs in which the threshold temperature for heating demand shifts towards lower temperatures from pattern A to D, while keeping other temperature dependent parameters, including the threshold temperature for cooling demand equal. Thus, the TDP in pattern B to D show a temperature independent plateau between these the threshold temperature for heating and cooling.

The results once more show similar trends as in previous scenarios. Neglecting a downward shift of heating demand threshold temperature thus results in an underestimation of energy demand. Neglecting an upward shift of this temperature however, results in overestimating energy demand.

Repeating this exercise with an increasing cooling demand threshold temperature and a stable heating demand threshold temperature results in exactly opposite trends. Neglecting an upward shift of cooling demand threshold temperature thus results in an overestimation of energy demand. Neglecting a downward shift of this temperature however, results in underestimating energy demand. Note that a decreasing T_{bH} has limited effect in warm climates, where temperatures below T_{bH} do not occur frequently; in such climates, heating demand is relatively low, therefore total energy demand is relatively insensitive to changes in heating demand.

7.7. Discussion

7.7.1. Implications of model results

Our results show how differences in the TDP affect the effects of climate change on energy demand. We have modeled various changes in pattern parameters to represent possible socio-economic changes that may lead to a changing TDP. Our model calculates the difference in energy demand resulting from climate change in a static context. However, the comparison of the results in the scenarios provides a dynamic perspective, as discussed in section 7.5.

The first four scenarios maintain the general form of the degree days based approaches, in which heating and cooling demands are linear functions sloping downward or upward, respectively and are separated at one threshold temperature. The results of these scenarios show that a decreasing relative importance of heating demand (α), an increasing relative importance of cooling demand (β), and a downward shift of the threshold temperature ($T_{bH} = T_{bC}$), affect the modeled effects of climate change on energy demand in a similar fashion. Models that assume any of these three changes in the TDP project a higher energy demand after climate change than models that assume a fixed TDP. Obviously, changes in the opposite direction lead to opposite results. Therefore, when these changes are presumed to occur randomly and lead to cancellation of each others effects, neglecting the variability for the sake of keeping the model simple could be quite acceptable. However, there is reason to believe that the effects of expected global socio-economic development on the TDP are non-random, and will add to each others effects. The developments are expected to lead to increasing economic welfare globally. This increasing economic welfare may be expected to affect the TDP in a similar way throughout the world.

Firstly, cooling and heating demands depend on the prevailing climate pattern in a given region. In general, “warm” regions have little need for heating, whereas “cold” regions have little need for cooling. In regions that fall somewhere in between, both cooling and heating may be demanded. In general, cooling may be considered to be less essential for human survival than heating. Therefore, cooling demand may be regarded as a ‘luxury’, although more so in cold climates than in warm climates. Moreover, heating is often fueled by oil, natural gas or wood, which are generally more easily accessible than the electricity that is usually required for cooling. In any given region, existing heating demand is expected to be met with little regard for economic welfare, whereas cooling demand may be expected to be met depending on a combination of prevailing climate and economic capacity. Given the current global distribution of welfare and climate patterns, we may expect that much of the global heating demand is already manifest in the TDPs, whereas much of the global cooling demand is still latent.

Secondly, international climate policy has put energy efficiency high on the agenda in the most developed countries, in which heating demand is currently (still) more prominent than cooling demand. Technological developments for energy efficiency may therefore be expected to focus first on optimizing heating efficiency and only later on cooling efficiency. Efficiency improvements may thus be expected to reduce heating demand more than cooling demand in the near future. In the long run, the large potential for reduction of cooling demand may be addressed. Nonetheless, we expect the increase in cooling demand to be more important for the temperature dependence of cooling demand than the decrease due to efficiency improvements. After all, if there is little cooling demand, there is little incentive to improve its efficiency.

Lastly, economic development generally leads to more electric appliances operated indoors. Therefore internal heat gains are expected to increase with economic development. These heat gains lead to downward shift in the threshold temperature, due to a decrease of heating demand and an increase in cooling demand.

Thus, economic development may be expected to lead to an increasing cooling demand, a possible decrease of heating demand and a downward shift of the threshold temperature. As we have seen from our modeling results, these changes of the TDP all lead to underestimation of future energy demand in models that do not accurately incorporate them.

Scenarios 5 and 6 diverge from the general form of degree days based models; either one of them adds an additional parameter to the model, which makes the model slightly more complex, but allows better incorporation of the developments described in section 7.2. Scenario 5 adds the idea of continuous temperature demand. Its results show that the additional continuous temperature dependent demand parameter γ behaves similarly as changing heating demand and cooling demand simultaneously. Because of this double effect, relatively small changes in continuous temperature dependent demand may have a relatively large impact on the effects of climate change on energy demand. Current models based on the degree days approach neglect this continuous temperature dependent demand, although they could incorporate it by estimating its effect on the modeled heating and cooling demands.

Scenario 6 splits the threshold temperature parameters into separate parameters for heating and cooling, so that the temperature ranges for heating and cooling demands may vary independently. This allows modeling the behavioral changes that influence the comfort zone depicted in Figure 7.1, such as e.g. a societal trend to dress lightly in winter or to overdress in summer, which could lead to a higher threshold temperature for heating and a lower threshold temperature for cooling. The scenario shows that a decreasing comfort zone can influence the expected effect of climate change on energy demand. However, since most current studies do not include such a comfort zone, they cannot model such trends.

The results further show that changing the parameters that influence heating demand results in larger differences in relatively cool climates whereas changing the parameters that influence cooling demand results in larger differences in relatively warm climates. This finding can be explained by the relative shares of heating or cooling demand in cold or warm climates respectively; e.g. the effect of an increased importance of cooling demand will be relatively limited in a relatively cold climate, since on most days there is no cooling demand anyway. In a relatively warm climate however, the effect of such a change would be much more pronounced.

7.7.2. General Discussion

Summarizing, the results from the linear model point to the importance of a correct representation of the future TDP when modeling the future energy demand resulting from climate change. A misrepresentation of the TDP may result in a misrepresentation of the projected effects. We argue that socio-economic dynamics may systematically alter the TDP in such a way that the results of studies not including such dynamics may underestimate the projected future energy demand resulting from climate change.

Therefore, we propose that future energy demand models should consider dynamically modeling each of the parameters α, β, γ, T_{bH} and T_{bC}, because our model results show that variation in each of these parameters may influence the model results. Various studies already include some dynamics in temperature dependence of heating and cooling demands. E.g. Isaac and Van Vuuren [2009] dynamically model various indicators that influence the energy demand per degree day for heating and cooling, such as floor space area, heating and cooling efficiencies and penetration rate of air conditioning. These indicators are supposed to vary with GNP, climate pattern and in time. Energy demand per degree day corresponds to the temperature dependence parameters α and β used in this chapter. Belzer et al. [1996] include a changing α, β, T_{bH} and T_{bC} in their model of the commercial sector in the USA. Unfortunately, this approach is highly data intensive, which makes extending it to the global scale virtually impossible. Moreover, it is based on regression analysis, which cannot adequately project the future. We suggest that a viable combination should be developed, in which the parameters that are modeled bottom up by Belzer et al. are based on top down indicators as in Isaac and Van Vuuren. Since Isaac and van Vuuren have already incorporated dynamics in α and β, we believe only limited additional adaptation would be required. Until the bottom-up parameters are effectively linked to top-down indicators, one could still estimate the key parameters in dynamic models from regression, but try to estimate in which way future societal development may influence them. Such estimation and an accompanying error-analysis may at least provide insight in possible errors resulting from socio-economic change.

Furthermore, we propose that future energy demand models should not convert temperature to degree days. We believe that such conversion is not necessary to describe a functional relation between outdoor temperature and energy demand and unnecessarily limits modeling the dynamics because of the described limitations of the degree days concept. Instead, this relation could be described directly from meteorological data, which enables varying the threshold temperatures T_{bH} and T_{bC}. Additionally, modeling temperature dependent energy demand without the degree days concepts enables the inclusion of continuous temperature dependent demand, by dynamically modeling γ. Modeling the threshold temperature variation, as well as the variation of the other parameters, requires further research to assess their relation with top down indicators such as technological development, GNP and climate zone, which in turn may influence effective space conditioned area, level of insulation, human comfort patterns, etc..

Our results are relevant for both warm and moderate climates. The largest socio-economic developments are expected in regions with a warm climate. Static modeling of the TDP in these regions may therefore lead to the largest errors. Moreover, our results suggest that global developments may lead to a shifting balance climate. Since such a shift may mean the difference between an expected decrease or increase in energy demand as a result of global warming, the results are also relevant for regions that are currently at or near the balance climate.

Furthermore, our analysis of the socio-economic dynamics of the TDP points towards an expected increasing importance of cooling demand throughout the world although we have not numerically analyzed this. Rapid developments will enable the increased application of cooling for space conditioning and food security in warm but currently poor regions. The increasing number of electric appliances producing indoor heat and the possible occurrence of heat waves in further developing rich countries in moderate climates may also lead to an increasing use of cooling applications in these regions, especially with expected climate change in mind.

The effects of such socio-economic developments on total regional or global energy demand probably are much larger than the effects of climate change as such. However, given the challenge of keeping global energy demand within its greenhouse limits, any additional percentage of demand may be relevant. Given the expected large increase in cooling demand globally and the generally long lifetime of buildings, efforts to analyze expected heating and cooling demands are essential for projecting the building constructions required to meet this growing demand with optimal energy efficiency. Moreover energy efficiency improvements of cooling as well as heating appliances may reduce the existing as well future expected energy demand.

7.7.3. Methodological discussion of the model

Our scenarios aim to show the effects on energy demand of changes in the TDP due to possible socio-economic developments in order to make modelers aware of the deficits of currently used methodologies. Preferably, data on the actual effects on TDP of such structural changes should have been used. However, no studies that numerically link changing TDPs to structural changes are known to the authors. Therefore, the model uses hypothetical, relative TDPs to investigate the effects of possible socio-economic changes. The relative TDPs we have modeled may not represent any existing TDP. Still, relative TDPs may take many different shapes in different regions; the slopes of the various types of temperature dependent demand depend on the relative contribution of temperature dependent applications to the total energy demand. Changes in the slopes of the TDPs therefore occur from relative volume changes. The values for α, β, γ, TbH and TbC may vary considerably between countries with different socio-economic structures in different world regions. The values used for α and β in the scenarios have been chosen to represent a conceivable range around the observed slopes in the graphs of Valor et al. [2001]. The values used for γ, TbH and TbC also represent realistically the ranges we may expect to find in various socio-economic systems. Thus we believe that the used set of TDP estimations is sufficiently extended for the stated purpose of methodological discussion. Further research should investigate the actual numerical relation between the parameters and the socio-economic system in order to enable actual future energy demand forecasts.

Various studies suggest that besides temperature, weather variables such as relative humidity and wind speed may also influence energy demand and in turn may also be influenced by climate change. However, in order not to burden the model and the discussion, our model considers only temperature.

Any simplification to model the TDP may impose restrictions upon the pattern's characteristics and the model's ability to include possible socio-economic developments. Other approaches that correlate demand variation with temperature variation try to capture the u-shaped relation in non-linear functions [Bessec and Fouquau, 2008; Moral-Carcedo and Vicéns-Otero, 2005]. These approaches are said to better fit the energy demand projection to observed demand, and may thus perform better in present energy demand forecasts. Bottom up analysis also suggests that heating and cooling demand may principally be non-linearly related to outdoor temperature [Henley and Peirson, 1997; Scott et al., 1994]. Principally, non-linear patterns could also be used in long term demand forecasts, however, no such attempt is currently known to the authors. Moreover, such approaches do not automatically generate better possibilities to include socio-economic developments than the simpler linear approach does. Therefore we restricted our assessment to linear dependencies.

In the TDPs resulting from our model, energy demand increases unlimitedly at the extreme ends of the temperature spectrum. Actual socio-economic systems will be limited by physical boundaries. In reality energy demand may level off towards the extreme ends of the temperature spectrum. Since most systems are expected to be adapted to their specific climate pattern, such occurrences may be rare and thus have only limited influence on total energy demand. Therefore, we believe our unlimited model approach adequately captures total energy demand.

Lastly, our model aggregates annual energy demand for heating and cooling. In reality heating and cooling demands are often met by different energy carriers, e.g. natural gas and electricity. A decreasing heating demand and an increasing cooling demand as a result of climate change therefore influences the relative shares of these energy carriers. Moreover, climate change may change the temporal distribution of demand throughout the year, including peak demand. Our model does not address any one of these issues.

7.8. Conclusion

This study has investigated the possible effect of socio-economic changes on the TDP of present and future energy demands in the context of climate change in order to improve future energy demand models. First we have analyzed the temperature dependence of heating and cooling demands. We investigated the interaction between the socio-economic structure and the TDP of energy demand. We concluded that socio-economic changes may alter the TDP in various ways.

Next we have analyzed how current studies approach these dynamics in socio-economic structure. We found that most studies misrepresent the possible dynamics in their models to assess the effect of climate change on future energy demand, although some studies do include some dynamics. The misrepresentation stems partly from simply neglecting the possible dynamics altogether and partly from using degree days as a basis for long term demand forecasting, which unnecessarily restricts variation in some key parameters that determine the TDP.

Finally, we have assessed the consequences of these misrepresentations in an energy demand model based on temperature dependence and climate scenarios. We argue that generally, future socio-economic developments may be expected to result in increasing cooling demand, possibly decreasing heating demand and a downward shift of threshold temperatures. Our model results indicate that such dynamics lead to an underestimation of future energy demand in models that misrepresent them. We therefore conclude that future energy demand models should incorporate socio-economic dynamics. We propose dynamically modeling several key parameters that are lacking in currently existing approaches, such as threshold temperature and continuous temperature dependent demand, and using direct meteorological data instead of degree days. However, future research should clarify the relations between socio-economic developments and these parameters to implement them successfully.

8. SYNTHESIS, CONCLUSIONS AND REFLECTIONS

The main research question of the thesis is:

> *"What are the consequences of the interaction between physical, socio-economic and policy systems for mitigating high-GWP refrigerant emissions in an effective long term climate strategy?".*

The preceding chapters 2-7 each document an individual study related to the interaction between refrigeration and air conditioning use, its environmental consequences and related policy approaches. Each of the chapters draws meaningful conclusions in its own right, which contribute to partly answering the main research question in the thesis. However, as noted in the introduction, fully answering the main question requires a comprehensive understanding of the issues involved from a multidisciplinary, spatially variable and temporally dynamic perspective.

This final chapter therefore explores the cross-links between the chapters, especially those in the thesis' first part, regarding refrigerant emission policy (chapters 2-5). It integrates the chapters' conclusions which results in the emergence of a multidimensional analytical framework that enables to draw a robust final conclusion. The chapters' 'synthesis' section first describes the various dimensions that constitute the analytical framework to assess refrigerant use in climate policy. It proceeds by summarizing and discussing the findings in each of the chapters in the perspective of this framework, marking cross-links between the findings. For reasons of completeness, the synthesis section also discusses the findings in chapters 6 and 7, although these are not presented within the scope of the analytical framework. These two chapters that form the second part of the thesis contribute to answering the related research question:

> *"Can increasing refrigeration and air conditioning use be observed in past energy demand and how can such changes be included in global energy demand models?".*

The comprehensive understanding of causes and consequences of current and future refrigerant emissions resulting from the synthesis enables answering the research questions in the chapters' 'conclusion' section. Finally the 'reflections' section reflects upon the findings of the thesis and puts them into a broader perspective.

8.1. Synthesis

8.1.1. Analytical framework

As noted above, the first part of the thesis approaches the main research question along various dimensions. Note that each chapter generally incorporates aspects of interdependencies with other dimensions; none of the chapters focuses on one dimension only.

The first dimension describes the triangular relation between the use of refrigeration and air conditioning applications in the socio-economical system, its environmental (physical) consequences and related regulatory policy approaches ('SEEP-triangle', see Figure 8.1). The thesis regards the environment and socio-economic activities as being mutually interdependent. It regards environmental policy to be mainly reactive, responding to observed or anticipated environmental impacts by influencing socio-economic activity. Policy may also reflect on the socio-economical system itself. The thesis thus regards policy as a special agent that can only indirectly influence the environment through its influence on socio-economic activities.

The second dimension describes the temporal dynamics in the SEEP-triangle. Autonomous and deliberate socio-economic, environmental and policy developments make the interactions within society dynamic. The future extent and valuation of the environmental consequences of GHG emissions from refrigeration and air conditioning may therefore differ from the present ones, which may induce introduction or adaptation of (additional) policy. The thesis therefore looks ahead into the future in order to enable timely action with regard to possible future environmental degradation. In order to better understand the possible futures, the thesis also reflects on historic developments.

The third dimension describes the spatial variation and interconnections within the (dynamic) SEEP-triangle. There are differences between the societal system in industrialized countries and in developing countries, which may lead to differentiated interaction between socio-economic activity, the physical environment and policy at different locations. Moreover, the dynamics in industrialized and developing countries

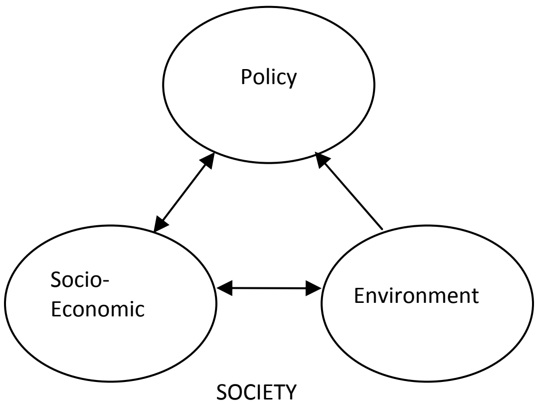

Figure 8.1 The SEEP-triangle, relating between socio-economic, environmental and policy systems within society.

may be expected to differ. Nonetheless, even though greenhouse gas emissions originate locally, the related climate change is occurring globally. Moreover, a broader perspective reveals that different local socio-economic, physical and policy systems are interconnected at the global scale, and are therefore mutually interdependent. Still, policies to address GHG emissions and ozone depletion globally may have differentiated effects locally. The thesis therefore investigates the consequences of local variation on the (future) environmental effect of local societal systems, their influence at the global system scale and also discusses the consequences of global policies on these local systems and the interaction between them.

Figure 8.2 presents graphically how each of the chapters 2-5 explores part of the theoretical three dimensional framework described above. It reflects that the extent to which each chapter focuses on the various dimensions varies and also the extent to which the conclusion of each chapter points towards the thesis' final conclusion. The discussion in this final chapter shows that the findings of each chapter strengthen each other, which makes the thesis' final conclusion more robust.

The second part of the thesis (chapters 6 and 7) focuses on the relation between energy demand and climate. It discusses societal dynamics from a local and a global perspective. As such it forms a part of another multidimensional framework related to energy consumption. However, the research question that this second part of the thesis

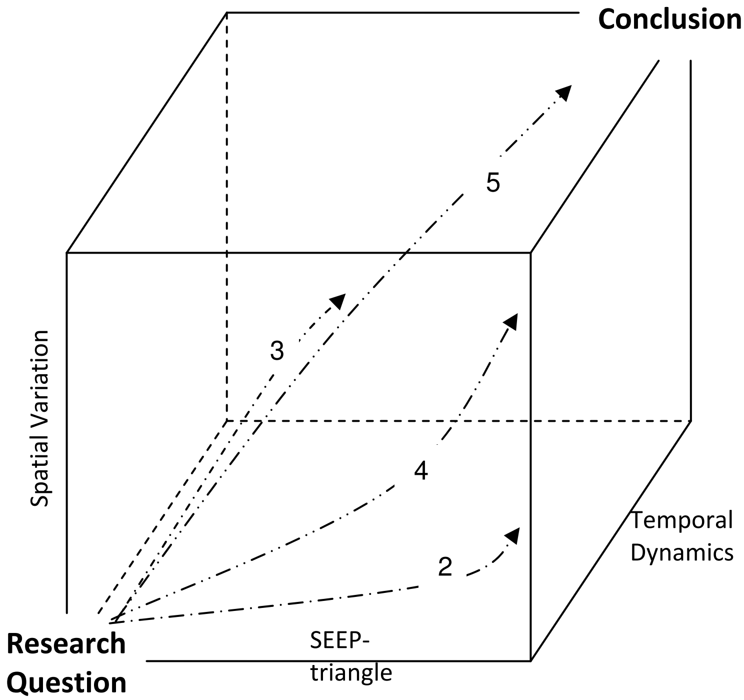

Figure 8.2 graphical representation of the theoretical three-dimensional framework explored in the thesis and the focus and contribution of chapters 2-5. The paths of the arrows represent the focus of each of the chapters, the position and direction of the arrowheads represent the extent to which the chapters findings point toward the final conclusion.

addresses does not require such a comprehensive assessment. Therefore the second part takes a more traditional analytical approach in which empirical research on the dynamics of electricity demand is combined with theoretically discussing approaches to capture such dynamics in global energy demand models.

8.1.2. Global policy effects on local stakeholders

Chapter 2 addresses the question

'Does climate policy design influence stakeholder cooperation?'

The chapter discusses the differences in policy design between the Montreal Protocol and the Kyoto Protocol and the possible consequences of such differences for policy effectiveness. It introduces the key characteristics of the Montreal Protocol and the Kyoto Protocol. Both these Protocols are important international agreements with regard to refrigerant emissions. The chapter discusses the protocols' effectiveness qualitatively, without a special focus on the refrigeration and air conditioning sector. Quantitative assessments of refrigerant emissions and their relation to both protocols follow in subsequent chapters.

The chapter places the role of local stakeholders at the heart of the discussion of global policy, arguing that ultimately, the environmental effectiveness of global policies depends on local stakeholders' active response to change the physical consequences of their socio-economic activities.

Based on social dilemma theory, the analysis presumes that stakeholders are less cooperative in larger groups and under higher uncertainty. It finds that the policy design in the Kyoto Protocol, compared to that in the Montreal Protocol, leads to larger groups of stakeholders that are collectively responsible to reach the policy target. Furthermore, it finds that policy design in the Kyoto Protocol leads to higher levels of uncertainty for the stakeholders involved. Lastly, it finds that the Kyoto Protocol allows a higher number of options through which its target can be achieved. However, since not all of these options are available to all individual stakeholders, individual perceived control may be reduced, which may also lead to lower cooperation. The chapter argues that some of the design distinctions between the Kyoto Protocol and the Montreal Protocol are due to intrinsic differences. The latter are defined as differences in the physico-chemical mechanisms resulting in climate change or ozone depletion, and in the function of and dependence on GHGs and ozone depleting substances (ODSs) in society. In the light of the SEEP-triangle described in the previous section, intrinsic differences may be interpreted as differences in the way the socio-economic system is interlinked with the physical system. Such differences may predefine the possibilities for policy design and thus limit the options for policy adjustment. Other design distinctions are argued to be political choices and thus more open to adjustment.

Based on its analyses the chapter points to several policy adjustments that may lead to improved stakeholder cooperation and may thus increase the policy effectiveness of the Kyoto Protocol. The findings suggest that setting substance-based or sectorial targets may help to reduce the group size of stakeholders collectively responsible to reach the target. In turn this may increase perceived efficacy and may reduce uncertainty with regard to the required effort each stakeholder is supposed to make. Such an approach may be part of an encompassing policy strategy to set up and manage a (national) GHG budget for all (or some) socio-economic sectors, comparable to the present financial budgets. This finding may be interpreted with regard to the refrigeration and air conditioning sector. Setting e.g. a specific target (or phase-out scheme) for HFC consumption similar to that for CFCs and HCFCs in the Montreal Protocol, or setting a target for emissions from the refrigeration and air conditioning sector may signal stakeholders that the sector's future depends on its success in reducing F-gas emissions. The chapter thus shows the added value of including the local characteristics of the SEEP-triangle in a global policy discussion.

8.1.3. The climate consequences of local developments regulated under global policy

Chapter 3 addresses the question

> *'What consequences does the Montreal protocol have for the global warming potential of fluorinated refrigerant emissions in rapidly developing China?'*

The chapter quantitatively discusses developments in the refrigeration and air conditioning sector in China. It describes the effects of the Montreal Protocol on these developments and places their consequences in the context of global climate policy. It thus links the effects of global policy on local development and the effect of local development on global policy. It elaborates and quantifies the environmental consequences of the use of fluorinated gases in the refrigeration and air conditioning sector. Its choice for China as a rapidly developing country contrasts with chapter 4 which deals with dynamics in Germany as an industrialized country. This contrast forms a representation of the spatial variation described in the analytical framework.

Chapter 3 finds that the expected rapid economic growth in China may result in a very large and rapid increase of F-gas emissions which is globally relevant. The use of HCFCs is expected to increase considerably, until the restrictions under the Montreal Protocol will bring about a transition to other refrigerants or technologies. If such transition develops similarly as that in industrialized countries, a large part of demand will be met by high GWP HFCs after the phase-out date, consequently leading to a rapid increase in the use and emission of HFCs in China. The emission rates projected in the chapter, in the order of 0.5 – 1 Gt CO_2-eq annually in 2030, are important at the global scale. An effective global climate policy, which aims at halving global emissions by 2050, can not afford to neglect such an important source of emissions, even more so because without active interference other developing countries may follow a similar developmental path.

The chapter also draws an interesting conclusion regarding the interaction between different policy strategies. The objective of the Montreal Protocol to prevent adverse effects of ozone depletion and the objective of climate policy to prevent adverse effects of global warming may find important synergies in the refrigeration and air conditioning sector. Nonetheless, any overlap between both objectives is avoided in policy documents, due to the current exclusion of ODS gases from the UNFCCC. The chapter finds that excluding ODS in the climate accounting considerably underestimates the contribution of fluorinated gas emission to the GHG emission total. The exclusion may therefore result in underestimating the importance to prevent and reduce F-gas emissions and may result in neglecting reduction options of perhaps global significance. This finding marks the interaction between the systems within the SEEP-triangle and places the triangle in a dynamic context.

8.1.4. The effect of policy on the climate consequences of local developments

Chapter 4 addresses the question

> *'What consequences do various mitigation strategies have on the emissions of HFC refrigerants in Germany?'*

The chapter quantitatively discusses the effect of different policy strategies on expected HFC emissions in Germany, which serves as a model for industrialized countries. It models the physical stock-flow properties of HFC use and emission in the refrigeration and air conditioning sector in this country. It describes the interaction in the SEEP-triangle between policy and its consequences on the environment through its effect on the physical base of the socio-economic system. Furthermore, it introduces dynamics into the triangle, mainly resulting from policy intervention. It introduces the ongoing debate on different refrigerant policy strategies and analyzes the consequences of following either a containment or a phase-out strategy.

The chapter suggests that the effects of a containment strategy may be expected to occur faster, because the strategy can directly target all refrigeration and air conditioning systems. The effects of a phase-out strategy may be expected to occur slower, because the strategy may not target existing systems and thus depends on the turnover of refrigeration and air conditioning systems. In the short run, emissions from a containment strategy may therefore be expected to be lower than emissions from a phase-out strategy. Still, the chapter finds that a phase-out strategy may be more effective in the long run, because it may prevent stock build up and hence emissions from future stock. It should be noted that the chapter does not elaborate on the absolute effectiveness of both strategies. Therefore, the chapter does not allow comparing the expected effectiveness of both strategies. Instead, the chapter investigates the temporal reduction patterns that result from each strategy.

The chapter further finds that early and quick implementation of an emission reduction strategy considerably reduces cumulative emissions over the modeled period. This is especially notable for a phase-out strategy, because in such a strategy stock build up is prevented. This timing effect is found to be less pronounced for containment strategies. This finding is highly relevant for policy implementation in developing countries, in which HFC stocks are still relatively low but may be expected to rise rapidly as shown in chapter 3.

The chapter further identifies several barriers in the socio-economic system that may result in a low policy preference for a phase-out strategy. The first barrier is a preference of policy makers for short term results. E.g. the Kyoto Protocol targets are set for the 2008-2012 timeframe; containment can contribute to reaching the targets, whereas phase-out has only minimal effects at this time scale. Secondly, the temporal cost distribution of the two strategies differs. Phase-out may require large (upfront) investment costs for system manufacturers to develop systems based on alternative refrigerants or new technologies. Such investment cost may raise the price of refrigeration and air conditioning systems, thus confronting users with higher (upfront) purchase prices. Containment may result in additional costs for better servicing and maintenance during the operation of the system, which are spread over the life time of the systems. Discounting the costs further ahead in time may lead to an economic preference for containment strategies.

The chapter suggests that if these barriers result in the selection of a containment strategy initially, this initial choice may lead to a lock-in situation, because the resulting emission reduction may reduce the perceived need for further emission reduction by a strategy change. The findings in chapter 5 underscore the global importance of the consequences of this suggestion.

8.1.5. The global interaction between local socio-economic, policy and physical systems

Chapter 5 addresses the question

> *'Which policy strategies can be effective in mitigating high global warming potential refrigerants globally, taking into account the various conditions set by the physical, socio-economic and policy systems?'*

The chapter qualitatively investigates how the variation in socio-economic and institutional systems between developing and industrialized countries influences the global opportunities to control emissions from the refrigeration and air conditioning systems. The chapter analyzes policies to reduce refrigerant emissions by investigating their consequences from a global governance perspective. The chapter distinguishes the different characteristics of stakeholders involved in refrigeration and air conditioning systems. Furthermore it differentiates between the situation in industrialized and developing countries.

The chapter acknowledges that different policy strategies set different prerequisites for their effective implementation and that different policies may have different consequences for the stakeholders involved. It discusses several current policy approaches to reduce refrigerant emissions. It investigates containment and technology shift[1] strategies and distinguishes market based and command and control based policy instruments to effectuate them. The chapter concludes that containment strategies have little chance to be effectively implemented globally, because implementation in developing countries may not be feasible. Technology shift strategies may prove to be more effective, provided that the cost of the implied technology development is borne mainly by industrialized countries.

A containment strategy requires sufficient cooperative capacity mainly at the level of system operators, and installation and maintenance engineers, in the form of e.g. education or financial capacity. A containment strategy also requires a well-functioning collection and destruction system for disposed refrigerants. Furthermore, a containment strategy requires sufficient institutional capacity to enforce the legislation throughout a country. The chapter suggests that such capacity may not be available in developing countries. Moreover, because a large number of mainly local stakeholders is involved in a containment strategy, it is difficult to support containment in developing countries by policy measures in industrialized countries. Therefore, a containment strategy may not be effectively implemented in developing countries.

A technology shift strategy requires capacity at the level of refrigeration and air conditioning system manufacturers, in the form of e.g. investment capital for technology

[1] In the thesis, the term 'technology shift strategy' is identical to the term 'phase-out strategy'. A phase-out strategy requires technology shift to provide alternative refrigeration and air conditioning systems. Reversely, a technology shift strategy is considered to lead to a phase-out of F-gas use, provided that the new technologies do not use F-gases.

development. There are relatively few system manufacturers and they are often multinational companies operating at the global market level. The chapter suggests that these characteristics enable policy in industrialized countries to influence system manufacturers. At the local level, a technology shift strategy may result in higher purchase prices to cover the investment cost for system manufacturers. Moreover, alternative systems may have higher production costs in general, e.g. because of different material requirements and (initially) lacking economy of scales. The chapter suggests that perhaps such additional costs may need to be covered by industrialized countries in some way, because such additional costs may form a barrier to realize a technology shift strategy in developing countries. International financial mechanisms such as the Clean Development Mechanism can possibly realize such financial transfer. Alternatively, a time-schedule could phase-in command and control legislation which differentiates between industrialized and developing countries. Such a differentiated schedule may lead to the necessary technology development and maturation of production facilities to supply industrialized countries first, which facilitates implementation in developing countries afterwards.

Thus, chapter 5 comprehensively addresses each of the three dimensions in the analytical framework and comes close to finding the answer to the main research question by itself. Nonetheless, the quantitative underpinning and exploration of social mechanisms provided in the earlier chapters complement the findings in this chapter and strengthen its case so that the main research question can be robustly answered (see section 8.2).

8.1.6. Local developments and their consequences of on local energy demand

Chapter 6 forms the first chapter of the second part of the thesis. It addresses the question

> *'Which changes can be observed in the temperature dependence of electricity demand in the Netherlands?'*

The chapter investigates the correlation between outdoor temperature and electricity consumption in the Netherlands from 1970 to 2007. It finds that historically, the correlation between temperature and electricity consumption in the Netherlands was generally negative in all months throughout the year. Thus, a higher temperature generally resulted in a lower electricity consumption in the past. Over time, this temperature dependence of electricity consumption is found to shift during summer months, resulting in a positive correlation in recent years. Currently a higher temperature thus generally results in higher electricity demand during summer months. The chapter suggests that the observed shift in temperature dependence may result from the increasing use of refrigeration and air conditioning systems. The chapter further discusses the possible implications of this trend for power generation and its planning with regards to future climate change.

The chapter's findings suggest that electricity consumption during summer months may increase in case of a rise in average temperature, possibly leading to a small summer peak in electricity consumption. Electricity consumption during winter months may be expected to decrease in case of higher average temperature. Because electricity consumption during winter months is generally higher than consumption during summer months, the overall effect of global warming on electricity consumption in the Netherlands may be a decrease. Still, the relative shift of consumption from winter to summer months may have implications for power generation planning and economics. Reduced cooling capacity in power plants due to warmer river water may increase electricity production cost in summer. More electricity use during summer months may thus lead to higher electricity prices. The chapter indicates that the generation pattern of solar power generation generally coincides with higher temperatures and may thus help in meeting future additional electricity demand from refrigeration and air conditioning systems at higher temperatures.

8.1.7. The influence of local developments on the consequences of climate change on global energy demand

Chapter 7 addresses the question

> *'How may the temperature dependence of energy demand be expected to change in the future and how do current energy models accommodate for such changes?'*

The chapter presents a theoretical background for modeling energy demand based on its temperature dependence, which is regularly used to estimate the effects of climate change on future energy demand. The chapter discusses underlying mechanisms for regularly observed 'u-shaped' temperature dependence patterns, based on the energy requirement to maintain indoor space temperature within a preference 'comfort zone'. It then proceeds to discuss how societal developments may influence energy demand through these mechanisms and translates them to possible changes of the temperature dependence pattern. The chapter discusses how various studies deal with modeling such changes. It finds that many studies are based on the 'degree days' concept, and discusses how using this concept as the base for each of these studies may misrepresent certain societal developments.

The study concludes by analyzing the effect of misrepresenting changes in the temperature dependence pattern on future energy demand projections. It finds that misrepresenting the development of the temperature dependence pattern in models to study the impact of climate change on global energy demand may lead to misestimating future energy demand. Notably, it finds that the effects of expected societal developments, such as increasing cooling demand, possibly decreasing heating demand and a downward shift of balance temperatures, may result in structural underestimation of future energy demand in the existing models. The chapter therefore suggests that future energy demand models should be adapted to enable the dynamical modeling of several key parameters that are currently misrepresented.

8.2. Conclusion

The analyses presented in chapters 2 to 5 show that the interaction between physical, socio-economic and policy systems has important consequences for an effective long term climate policy. The thesis' main conclusion is:

> *Because of the global interconnectedness of the socio-economic, physical and policy systems, an effective long term climate policy should aim at globally phasing out high GWP refrigerant use, starting in industrialized countries.*

The analyses presented in chapters 6 and 7 show that increasing use of refrigeration and air conditioning systems may lead to changes in the temperature dependence pattern of energy demand. A related conclusion of the thesis is:

Increasing use of refrigeration and air conditioning systems may change the temperature dependence pattern of electricity demand. Global energy demand models that address future energy demand in the context of climate change should accommodate such and other socio-economic developments by dynamically modeling the temperature dependence pattern.

Greenhouse gas emissions from refrigeration and air conditioning systems may be expected to contribute importantly to future global GHG emissions. The analysis of future emissions in China in chapter 3 underscores the importance of a globally effective approach to refrigerant emission control that acknowledges developments in developing countries. Refrigerant emissions in China alone may contribute significantly to the global total GHG emissions. Other developing countries, which together harbor most of the world population, may follow a similar development pathway as that projected for China. The importance of controlling future refrigerant emissions from developing countries is therefore paramount. Many industrialized countries have already implemented regulatory policies and thus generally report much lower emission rates, as seen in chapter 4, which may suggest that refrigerant emissions are less relevant in their climate policies. However, as is noted in chapter 5, if industrialized countries are serious about their 'common but differentiated' responsibility to reduce global GHG emissions, they should facilitate GHG reduction paths in developing countries, by enabling transfer of effective technology and or effective policies.

Chapter 4 shows that the timing of emission reduction strategies is important. Climate change ultimately results from cumulative emissions, which means that the sooner emissions are reduced, the more climate change is being prevented. Moreover, the use of a certain type of refrigeration technology commits the system's type of refrigerant emission for up to several decades. Effectuating a timely and rapid transition to low GWP refrigerants or alternative technologies can prevent building up a stock of high GWP gases, and thus prevents getting committed to their emissions. The findings in chapter 3 indicate that the upcoming phase-out of HCFCs in developing countries may provide a unique opportunity in this regard. Chapter 2 stresses the role of social processes in effective policy strategies. It suggests that a policy that improves individual stakeholders' commitment may be more effective than a policy that only outlines a temporally distant global target. It concludes that setting substance based or sectorial targets may increase stakeholder cooperation with climate policy. The refrigeration and air conditioning sector already has experience with such type of targets through its commitments under the Montreal Protocol, which have successfully reduced the use of ozone depleting substances in the sector. The role of stakeholders is further exemplified in chapter 5, which integrates the effectiveness of policy approaches from a global governance perspective. It suggests that the containment policy that is currently pursued in some industrialized countries may not be effective in developing countries, because individual stakeholders as well as institutions may not have sufficient capacity to effectuate the policy. The chapter suggests that a technological shift strategy, which leads to phase-out of high GWP refrigerants, sets requirements on different stakeholders which are better capable to effectuate the policy. Such strategy has recently been implemented in Europe for mobile air conditioning systems, and seems to have induced the required technology development, which bodes well for possible implementation in other sub-sectors.

Chapters 6 and 7 point out that energy demand from refrigeration and air conditioning is temperature dependent. Chapter 6 finds a changing temperature dependence pattern of electricity demand in the Netherlands and links this development to the increasing use of refrigeration and air conditioning systems. Chapter 7 shows the consequences of such changing temperature dependence patterns for modeling energy demand. It finds that many studies neglect the dynamics of the socio-economic system, which may lead to underestimating future energy demand. An important notion in this regard is that the increasing use of refrigeration and air conditioning systems obviously leads to increasing energy use. Although it does not play a major role throughout the thesis, the issues of refrigerant emissions and energy use may also make one to critically question the increasing use of refrigeration and air conditioning systems itself, especially in luxury uses and in countries with moderate summer temperatures.

8.3. Reflections

This thesis discusses the possible development of the refrigeration and air conditioning sector from the perspective of a long term global climate policy. It assumes a future society that functions under so called carbon constraints; in which countries, sectors, processes or individuals are allotted only a limited amount of GHG emission space per year. Like other scarce commodities, in a carbon constraint society 'using' emission space for one socio-economic activity ultimately means giving up another activity. This artificial scarcity may result in different consumptive and productive behavior in a future society compared to the present society. One might imagine that some currently prevalent activities with relatively high related GHG emissions may be replaced in such a society by different and less emitting alternatives. However, the exact composure of demand for and supply of certain activities in such a future society is currently indeterminable.

Even though some activities have a relatively large climate impact, current climate policy hardly states the preference for one activity over another. Although this position expresses the freedom of choice, it fails to express that the artificial scarcity created by limiting GHG emissions alters the relative (individual and societal) utility of different socio-economic activities. In a free society individuals should be allowed to choose how to meet their needs and wants according to their personal preferences. Still, in order to stay within a collectively allotted emission space, the consequences of individual's choices to meet certain needs or wants on the future (individual and collective) options to meet other needs or wants should be fed back into their decision making process in order to possibly influence it. From this perspective, climate policy may justifiably differentiate between activities with different climate performance.

As climate policy further develops and the remaining emission space[2] becomes smaller, the question on which activities to spend the remaining emission space may become more pressing and may also become politicized. Creating national carbon budgets, similar to financial budgeting, in order to regulate societally optimal use of emission space may be necessary in such case. The thesis suggests that sectorial or substance based targets, which may be regarded as budgets, may improve stakeholder commitment to achieving the collective target.

[2] Emission space refers to the amount of GHG emissions that can still be emitted until the atmospheric concentration reaches a certain agreed threshold level.

The thesis' suggestion to move away from using high GWP refrigerants may be regarded as a step into the direction of regulating the use of remaining emission space. As stated in the introduction (chapter 1), refrigeration and air conditioning contribute importantly to improving human health. Their utility to society is not questioned in the thesis. Whether their uses will be tenable in all of its current (and expanding) applications in a carbon constraint society, depends on their future performance and future consumptive preferences. Nonetheless, the thesis clearly shows the consequences of continuing to use refrigeration and air conditioning systems with their current climate performance. It is hard to conceive that continuing to use such systems optimizes societal utility under severe carbon constraints. A political statement that there is no place for current systems in a future carbon budget may decrease uncertainty for the stakeholders involved, and may invigorate them to (further) develop alternatives.

The thesis does not elaborate on the alternative refrigerants and technologies which are assumed to replace the currently dominant technologies using fluorinated gases in phase-out or technology shift strategies. It simply assumes that alternative systems will sufficiently be made available. The range of options that may be regarded alternative technologies varies widely from systems that are closely related to current ones (like similar systems with lower charges, secondary loop systems and systems using different (lower-GWP) refrigerants) to systems that use totally different technologies (like systems using the Stirling cycle, absorption cycle, thermoelectric cooling, thermoacoustic cooling or magnetic cooling). The thesis does not state preference for any specific technology and considers the extent to which technology shift is supposed to reduce emissions to be a matter of politics. Still, it may be obvious that the extent to which switching to any of these systems may reduce global high-GWP refrigerant emissions varies considerably.

Many of these alternatives have already been developed but are not yet used widely. The limited use may result from a higher price level, which may result from the fact that the production of systems containing fluorinated refrigerants has been optimized during decades of production and because some technologies require additional safety measures. Moreover, consumers often demand 'proven technologies', especially in the case of technologies that have to work continuously. This indicates that developing alternative systems hardly forms a technological problem but rather a socio-economic one; a technology shift will have to successfully pass the different stages that lead to successful innovation. Moreover, it indicates that policies that influence the relative utility of current and alternative systems based on their climate performance may speed up the introduction of and transition to systems with better climate performance.

Sometimes alternative refrigeration and air conditioning systems are said to lead to higher energy use than would be possible with fluorinated refrigerants. As long as the energy system has not been transformed into a fully carbon neutral system, the carbon emissions related to the higher energy use of such alternative refrigeration and air conditioning systems may therefore negate the gains from emitting less high GWP refrigerants. The thesis does not elaborate on this trade off. It assumes the future energy system will be carbon neutral. Still, given the projections of refrigerant emissions in the thesis, the transition towards alternative refrigeration and air conditioning systems should not wait until the completion of the energy transition. From this perspective, it seems prudent to set energy efficiency standards that minimize energy use alongside possible policy to induce the required technology shift. Minimizing energy use from refrigeration and air conditioning systems also contributes to limiting the potential problems related to shifting temperature dependence patterns discussed in the thesis.

The thesis also assumes that containment strategies will not be sufficiently effective in developing countries. Although this seems to be the case in many developing countries under current circumstances, socio-economic development over the coming decades may improve the regulatory capacity in such countries. Thus, containment strategies can possibly reduce future refrigerant emissions in developing countries. Still, building the required capacity may take decades, which means decades of continuing high GWP refrigerant emissions consuming part of the globally remaining emission space that could instead be used for other purposes.

Moreover, it remains questionable whether containment can sufficiently reduce emissions, given the expected increasing use of refrigeration and air conditioning systems in these countries, and given decreasing globally available emission space. Betting on a containment strategy as a sustainable solution for the refrigeration and air conditioning sector may therefore be regarded betting on very short odds.

The thesis' integrative perspective of local and global interdependencies helps to provide insights that might remain hidden in traditional environmental analyses at either a local or the global scale. Its discussion of the dependence of and requirements for individual stakeholders in the described governance system stresses the notion that aggregate GHG reduction targets have actual consequences in the socio-economic system. The relatively limited number of different stakeholders and processes in the refrigeration and air conditioning sector enables a meaningful connection between top down and bottom up policy analysis, which improves a comprehensive understanding of the issues at hand.

The notion that successfully managing global refrigerant emissions requires policies that effectively counter developments at each individual local level may simply confirm the need for a united global effort to mitigate GHG emissions in general. However, the thesis also finds that implementing a successful approach at one local level (that of a developing country) may require a facilitating approach at another local level (that of industrialized countries). Because the local situation in industrialized countries differs from that in most developing countries, industrialized countries may have options that are well consistent with reaching their own objectives but that would block an effective solution for developing countries. This notion signals that the issue of common but differentiated responsibility may signify more than setting common but differentiated emission targets. It suggests that an effective global climate policy may require global cooperation to develop synergetic pathways to resolve or circumvent local problems. It signals e.g. that the role of technology transfer may reach beyond simply transferring existing 'modern' technologies from industrialized to developing countries, but may also imply following new technological pathways that benefit developing countries as well as industrialized countries. Thus, effective global climate policy may need to prevent each country from following its individually optimal local solution and may need to aim at improving cooperation to collectively determine the optimal global solution. Assessing climate policy issues through the multidimensional and multidisciplinary analytical framework presented in the thesis may help to recognize possible bottlenecks and acknowledge possible collective approaches that may prevent sub-optimal lock in situations.

References

Chapter 1

Baer P, Athanasiou T, Kartha S, and Kemp-Benedict E (2008). *The greenhouse development rights framework*. Heinrich Böll Stiftung, Berlin.

Bodeker GE and Waugh DW (2006). *Chapter 6. The Ozone Layer in the 21st Century,* in Scientific Assessment of Ozone Depletion: 2006. Global Ozone Research and Monitoring Project-Report No. 50 pg. 6.1-6.43. World Meteorological Organization, Geneva.

Bressers JThA (2004). *Implementing sustainable development: How to know what works, where, when and how,* in Governance for sustainanle development: the challenge of adapting form to function (Lafferty WM (ed)). Edward Elgar publishing, Cheltenham.

Coase RH (1960). *The Problem of Social Cost*. The Journal of Law and Economics 3(1):1.

Crutzen PJ (2002). *Geology of mankind*. Nature 415(6867):23-23.

EPEE (2001). *HFCs, refrigeration and air-conditioning: Minimising climate impact, maximising safety.* http://www.epeeglobal.org/English/HFCdocs/HFCs_and_Refrigeration_brochure.pdf (retrieved 23-2-2009).

European Commission (2006b). *Regulation (EC) No. 842/2006 of the European Parliament and of the Council of May 17th, 2006 on certain fluorinated greenhouse gases*.

Fouillet A, Rey G, Laurent F, Pavillon G, Bellec S, Guihenneuc-Jouyaux C, Clavel J, Jougla E, and H+¬mon D (2006). *Excess mortality related to the August 2003 heat wave in France*. International Archives of Occupational and Environmental Health 80(1):16-24.

Gupta S and Tirpak DA (2007). *Chapter 13 Policies, Instruments and Co-operative Arrangements,* in Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (Metz B, Davidson OR, Bosch PR, Dave R, and Meyer LA (eds)). pg. 745-808. Cambridge University Press, Cambridge, UK and New York, USA.

Hardin G (1968). *The Tragedy of the Commons*. Science 162(3859):1243-1248.

IIR (2005). *Global warming: refrigeration-sector challenges. IIR Statement to the Eleventh session of the Conference of the Parties (COP11) and the First session of the meeting of the Parties to the Kyoto Protocol (COP/MOP1) .* http://www.iifiir.org/en/doc/1003.pdf (retrieved 27-4-2009).

IPCC (2007). *Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. IPCC, Geneva.

IPCC and TEAP (2005). *IPCC/TEAP Special Report on Safeguarding the Ozone Layer and the Global Climate System: Issues related to Hydrofluorocarbons and Perfluorocarbons.* Cambridge University Press, Cambridge and New York.

Klok PJ (1991). *Een instrumententheorie voor milieubeleid (Eng: An instrumentation theory for environmental policy). (dissertation)* Faculteit der Bestuurskunde, Universiteit Twente, Enschede.

KNMI (2008). *Daily weather data of the Netherlands.* http://www.knmi.nl/klimatologie/daggegevens/download.cgi?language=eng (retrieved 24-9-2008).

Maslow AH (1943). *A theory of human motivation*. Psychological review 50(4):370-396.

Meinshausen M (2005). *On the Risk of Overshooting 2°C*. Proceedings from International Symposium on Stabilisation of Greenhouse Gas Concentrations -- Avoiding Dangerous Climate Change .

Mitchell RB (2006). *Problem Structure, Institutional Design, and the Relative Effectiveness of International Environmental Agreements*. Global Environmental Politics 6(3):72-89. Massachusetts Institute of Technology, Massachusetts.

Molina MJ and Rowland FS (1974). *Stratospheric sink for chlorofluoromethanes: chlorine atom-catalysed destruction of ozone*. Nature 249:810-812.

PBL, CBS, and WUR (2007). *Milieu- en natuurcompendium. Mondiale emissie koolstofdioxide per sector, 1970-2004 (Eng: Environment and nature compendium. Global carbondioxide emission per sector, 1970-2004).* http://www.milieuennatuurcompendium.nl/indicatoren/nl0166-Koolstofdioxide-emissie%2C-mondiaal.html?i=9-20 (retrieved 27-4-2009).

Schenk NJ (2006). *Modelling energy systems. (dissertation)* University of Groningen, Groningen.

Schoot Uiterkamp AJM and Vlek CAJ (2007). *Practice and outcomes of multidisciplinary research for environmental sustainability*. Journal of Social Issues 63(1):175-197.

Schreuder Y (2009a). *The corporate greenhouse: climate change policy in a globalized world* . Zed Books, London / New York.

Smith JB, Schneider SH, Oppenheimer M, Yohe GW, Hare W, Mastrandrea MD, Patwardhan A, Burton I, Corfee-Morlot J, Magadza CHD, Füssel HM, Pittock AB, Rahman A, Suarez A, and van Ypersele JP (2009). *Assessing dangerous climate change through an update of the Intergovernmental Panel on Climate Change (IPCC) "reasons for concern"*. Proceedings of the National Academy of Sciences 106(11):4133-4137.

Steg L (2003). *Motives and behaviour in social dilemmas relevant to the environment,* in Human decision making and environmental perception. Understanding and assisting human decision making in real-life settings (Hendickx L, Jager W, and Steg L (eds)). pg. 83-102. University of Groningen, Groningen.

Ummels BC (2009). *Wind Integration. (dissertation)* Delft University of Technology, Delft.

UN (1987). *Montreal Protocol on Substances that Deplete the Ozone Layer*.

UN (1992b). *United Nations Framework Convention on Climate Change*.

UN (1997). *The Kyoto Protocol*.

UNEP (2005). *Supplement to the IPCC/TEAP Report*. UNEP, Nairobi.

UNEP (2007a). *2006 Report of the Refrigeration, Air Conditioning and Heat Pumps Technical Options Committee*. UNEP, Nairobi.

UNFCCC (2009b). *Website information UNFCCC.* http://unfccc.int/essential_background/convention/items/2627.php (retrieved 21-4-2009).

WMO (2007). *Scientific Assessment of Ozone Depletion: 2006 Global Ozone Research and Monitoring Project—Report No. 50*. WMO, Geneva.

Chapter 2

ARAP (2007). *HCFC Regulations.* http://www.arap.org/regs/ (retrieved 27-5-2009).

Biel A and Gärling T (1995). *The role of uncertainty in resource dilemmas*. Journal of Environmental Psychology 15(3):221-233.

Bord JB, Fisher A, and O'Conner RE (1998). *Public perceptions of global warming: Unisted States and international perspectives*. Climate Research 11:75-84. Inter-Research.

Carpenter JP (2007). *Punishing free-riders: How group size affects mutual monitoring and the provisioin of public goods*. Games and Economic Behaviour 60:31-51. Elsevier.

COP-13 (2007). *Bali Action Plan*. UNFCCC.

Dawson NL and Segerson K (2008). *Voluntary Agreements with Industries: Participation Incentives with Industry-wide Targets*. Land Economics 84(1):97-114.

De Cremer D and Leonardelli GJ (2003). *Cooperation in social dilemmas and the need to belong: The moderating effect of group size*. Group Dynamics: Theory, Research, and Practice 7(2):168-174. The Educational Publishing Foundation.

Dietz T, Ostrom E, and Stern PC (2003). *The struggle to govern the commons*. Science 302:1907-1912.

Dunlap RE (1998). *Lay perceptions of Global Risk*. International Sociology 13(4):473-498. Sage Journals.

EEA (1997). *Environmental agreements - environmental effectiveness*. European Environment Agency, Copenhagen.

European Commission (1996). *Communication to the council and the European parliament on environmental agreements*.

European Commission (2008). *Decision of the European Parliament and of the Council on the effort of Member States to reduce their greenhouse gas emissions to meet the Community's greenhouse gas emission reduction commitments up to 2020*.

Fahey DW (2007). *Twenty questions and answers about the ozone layer,* in Scientific assessment of ozone depletion: 2006 (Ennis CA (ed)). WMO, Geneva.

Farman JC, Gardiner BG, and Shanklin JD (1985). *Large losses of total ozone in Antarctica reveal seasonal ClOx / NOx interaction*. Nature 315(6016):207-210. Nature Publishing, London.

Fehr E and Gächter S (2000). *Cooperation and punishment in public goods experiments*. The American Economic Review 90(4):980-994. American Econoic Association.

Gore A (2006). *An Inconvenient Truth. The Planetary Emergency of Global Warming and What We Can Do About It* . Rodale Press, Emmaus.

Hardin G (1968). *The Tragedy of the Commons*. Science 162(3859):1243-1248.

Hauert C, Holmes M, and Doebele M (2006). *Evolutionary games and population dynamics: maintenance of cooperation in public goods games*. Proceedings of the Royal Society B 273:2565-2570.

IPCC (2007). *Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. IPCC, Geneva.

Iyengar SS and Lepper MR (2000). *When choice is demotivating: Can one desire too much of a good thing?* Journal of Personality and Social Psychology 79(6):995-1006. American Psychological Association, Washington D.C.

Jager W, Janssen MA, and Vlek CAJ (2002). *How uncertainty stimulates over-harvesting in a resource dilemma: Three process explanations*. Journal of Environmental Psychology 22:247-263. Elsevier Science Ltd.

Kerr NL (1989). *Illusions of Efficacy: the effects of group size on perceived efficacy in social dilemmas*. Journal of Expirimental Social Psychology 25:287-313.

Leiserowitz AA (2005). *American Risk Perceptions: Is Climate Change Dangerous?* Risk Analysis 25(6):1433-1442. Blackwell Synergy.

Little AD (2002). *Global Comparative Analysis of HFC and Alternative Technologies for Refrigeration, Air Conditioning, Foam, Solvent, Aerosol Propellant, and Fire Protection Applications*. Arthur D. Little Inc., Cambridge.

McCulloch A (1999). *CFC and Halon replacements in the environment*. Journal of Fluorine Chemistry 100(1-2):163-173.

Metz B, Berk M, Den Elzen M, De Vries B, and Van Vuuren D (2002). *Towards an equitable global climate change regime: compatibility with Article 2 of the Climate Change Convention and the link with sustainable development*. Climate Policy 2(2-3):211-230.

Molina MJ and Rowland FS (1974). *Stratospheric sink for chlorofluoromethanes: chlorine atom-catalysed destruction of ozone*. Nature 249:810-812.

NASA (2008). *Ozone Hole Watch.* http://ozonewatch.gsfc.nasa.gov/ (retrieved 13-5-2008).

Oberthür S (2001). *Linkages between the Montreal and Kyoto Protocols – Enhancing Synergies between Protecting the Ozone Layer and the Global Climate*. International Environmental Agreements: Politics, Law and Economics 1(3):357-377. Springer Netherlands.

Porter ME and Linde C (1995). *Green and Competitive*. Harvard Business Review September-October 1995:120-134. EBSCOhost.

Staat der Nederlanden (2003). *Besluit ozonlaagafbrekende stoffen milieubeheer (Eng: decision ozone depleting substances environmental conservation)*.

Steg L (2003). *Motives and behaviour in social dilemmas relevant to the environment,* in Human decision making and environmental perception. Understanding and assisting human decision making in real-life settings (Hendickx L, Jager W, and Steg L (eds)). pg. 83-102. University of Groningen, Groningen.

Stern N (2007). *Stern Review: The economics of climate change*. Cambridge University Press, Cambridge.

UN (1985). *The Vienna Convention for the Protection of the Ozone Layer*.

UN (1987). *Montreal Protocol on Substances that Deplete the Ozone Layer*.

UN (1992b). *United Nations Framework Convention on Climate Change*.

UN (1997). *The Kyoto Protocol*.

UN (2007). *Adjustment of the Montreal Protocol agreed at the 19th Meeting of the Parties*.

UNEP (2008). *Ozone Secretariat Data Access Centre.* http://ozone.unep.org/Data_Reporting/Data_Access/ (retrieved 13-5-2008).

UNFCCC (2008a). *Bangkok: First stop on the road to Copenhagen.* http://unfccc.int/meetings/intersessional/awg-lca_1_and_awg-kp_5/items/4334.php (retrieved 15-5-2008a).
UNFCCC (2008b). *National Inventory Submissions 2008.* http://unfccc.int/national_reports/annex_i_ghg_inventories/national_inventories_submissions/items/4303.php (retrieved 13-5-2008b).
UNFCCC (2008c). *The mechanisms under the Kyoto protocol: Emissions Trading, the Clean Development Mechanism and Joint Implementation.* http://unfccc.int/kyoto_protocol/mechanisms/items/1673.php (retrieved 19-5-2008c).
UNFCCC (2008d). *UNFCCC website information on the Kyoto Protocol.* http://unfccc.int/kyoto_protocol/items/2830.php (retrieved 13-5-2008d).
WMO (2007). *Scientific Assessment of Ozone Depletion: 2006 Global Ozone Research and Monitoring Project—Report No. 50*. WMO, Geneva.
WRI (2008). *Climate Analysis Indicators Tool (CAIT) version 5.0.* http://cait.wri.org/ (retrieved 13-5-2008).

Chapter 3

AFEAS (2004). *Production and Sales of Fluorocarbons.* http://www.afeas.org/production_and_sales.html (retrieved 18-8-2007).
Hafner A and Nekså P (2006). *Global environmental consequences of introducing R-744 (CO2) mobile air conditioning*. SINTEF Energy research, Trondheim.
IEA (2007). *World Energy Outlook 2007. China and India insights*. OECD/IEA, Paris.
IIASA (2007). *GAINS China and East-asia online.* http://gains.iiasa.ac.at/gains/EAS/index.login?logout=1 (retrieved 30-8-2007).
IPCC (2007). *Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. IPCC, Geneva.
IPCC and TEAP (2005). *IPCC/TEAP Special Report on Safeguarding the Ozone Layer and the Global Climate System: Issues related to Hydrofluorocarbons and Perfluorocarbons.* Cambridge University Press, Cambridge and New York.
McCulloch A and Lindley AA (2007). *Global emissions of HFC-23 estimated to year 2015*. Atmospheric Environment 41(7):1560-1566.
Tohka A (2005). *The GAINS Model for Greenhous Gasa - Version 1.0: HFC, PFC and SF6. Interim Report.* IIASA, Laxenburg.
UN (1987). *Montreal Protocol on Substances that Deplete the Ozone Layer*.
UN (1992b). *United Nations Framework Convention on Climate Change*.
UN (1997). *The Kyoto Protocol*.
UNEP (2007b). *Analysis and calculations on the various scenarios for accelerated HCFC phase out contained in the proposed adjustments of the Protocol – Submission by the Multilateral Fund Secretariat.* http://ozone.unep.org/Meeting_Documents/mop/19mop/MLF-Submission-on-HCFC-Adjustment-Proposals.pdf (retrieved 1-5-2009).
UNEP (2008). *Ozone Secretariat Data Access Centre.* http://ozone.unep.org/Data_Reporting/Data_Access/ (retrieved 13-5-2008).
UNFCCC (2009a). *Manufacturing and servicing of domestic refrigeration appliances using a low GWP refrigerant --- Version 1 (Methodology Approved by the CDM executive*

board). http://cdm.unfccc.int/UserManagement/FileStorage/CDMWF_AM_9R0HVQOIO2AWALYMLDBNAUH4ONCUEM (retrieved 30-3-2009).

Velders GJM, Andersen SO, Daniel JS, Fahey DW, and McFarland M (2007). *The importance of the Montreal Protocol in protecting climate*. Proceedings of the National Academy of Sciences 104(12):4814-4819.

Chapter 4

Anderson J (2005). *Is STEK as good as reported?* Institute for European Environmental Policy IEEP, Brussels.

Bivens DB (1999). *Refrigeration and air conditioning with reduced environmental impact*. Dupont Fluoroproducts, Wilmington.

Calm JM (2002a). *Emissions and environmental impacts from air-conditioning and refrigeration systems*. International Journal of Refrigeration 25(3):293-305.

Calm JM (2002b). *Options and outlook for chiller refrigerants*. International Journal of Refrigeration 25(6):705-715.

Clodic D and Palandre L (2004). *Determination of comparative HCFC and HFC emission profiles for the foam and refrigeration sectors until 2015. Part 1 - Refrigerant emission profiles*. Centre d'Energetique (Ecole des Mines de Paris/ Armines), Paris.

European Commission (2006a). *Directive 2006/40 of the European Parliament and of the Council relating to emissions from air conditioning systems in motor vehicles and amending Council Directive 70/156/EEC*.2006/40.

European Commission (2006b). *Regulation (EC) No. 842/2006 of the European Parliament and of the Council of May 17th, 2006 on certain fluorinated greenhouse gases*.

Fischer SK, Hughes PJ, Fairchild PD, Kusik CL, Dieckmann JT, McMahon EM, and Hobday N (1991). *Energy and Global Warming Impacts of CFC Alternative technologies*. AFEAS/ DOE, Washington DC/ Oak Ridge.

Ford AT (1999). *Modeling the Environment: an introduction to system dynamics models of environmental systems* . Island Press, Washington D.C.

Grace IN, Datta D, and Tassou SA (2005). *Sensitivity of refrigeration system performance to charge levels and parameters for on-line leak detection*. Applied Thermal Engineering 25(4):557-566.

Harmelink M, De Jager D, Kerssemeeckers M, Hendriks C, and Van Brummelen M (2002). *TEWI: Total Equivalent Warming Impact: a practical approach*. Non-CO2 Greenhouse Gases :627-632. Millpress, Rotterdam.

Harnisch J and Hendriks C (2000). *Economic Evaluation of Emission Reductions of HFCs, PFCs and SF6 in Europe*. Ecofys, Cologne.

Harnisch J, Stobbe O, and De Jager D (2001). *Abatement of Emissions of Other Greenhouse Gases: "Engineered Chemicals"*. Ecofys, Utrecht.

IPCC and TEAP (2005). *IPCC/TEAP Special Report on Safeguarding the Ozone Layer and the Global Climate System: Issues related to Hydrofluorocarbons and Perfluorocarbons.* Cambridge University Press, Cambridge and New York.

Johnson E (2004a). *HFC containment has already failed.* http://www.mipiggs.org/library/pdfs/hfccontainment.pdf. (retrieved 27-8-2009).

Little AD (2002). *Global Comparative Analysis of HFC and Alternative Technologies for Refrigeration, Air Conditioning, Foam, Solvent, Aerosol Propellant, and Fire Protection Applications*. Arthur D. Little Inc., Cambridge.

Meadows DA (1972). *The Limits of Growth. A Report for The Club of Rome's Project on the Predicament of Mankind.* Universe Books, New York.

Palandre L, Zoughaib A, Clodic D, and Kuijpers L (2003). *Estimation of the world-wide fleets of refrigerating and air-conditioning equipment in order to determine forecasts of refrigerant emissions*. The Earth Technology Forum , Washington.

Schaefer D, Godwin D, and Harnisch J (2006). *Estimating Future Emissions and Potential Reductions of HFCs, PFCs, and SF6*. Energy Journal 27:63-88. International Association for Energy Economics, Inc.

Schwarz W (2005). *Emissions and Emissionsprogosis of HFC, PFC and SF6 in Germany - Current situation and development of a system of annual investigation (in German: Emissionen und Emissionsprognose von H-FKW, FKW und SF6 in Deutschland - Aktueller Stand und Entwicklung eines Systems zur jährlichen Ermittlung)*. Öko-recherche, Frankfurt/Main.

STEK (2002). *Koudemidelgebruik in Nederland (Eng: Refrigerant use in the Netherlands)*. STEK, Utrecht.

Sterman JD (2002). *All models are wrong: reflections on becoming a systems scientist*. System Dynamics Review 18(4):501-531. John Wiley & Sons.

UBA (2004). *Fluorinated Greenhouse Gases in Products and Processes*. German Federal Environmental Agency, Berlin.

UBA (2006). *Common Reporting Format Emission Inventory Tables for Germany 1990-2004*. German Federal Environmental Agency.

UN (1992). *United Nations Framework Convention on Climate Change*.

UN (1997). *The Kyoto Protocol*.

UNEP (1987). *Montreal Protocol on Substances that Deplete the Ozone Layer*.

UNEP (2002). *2002 Report of the Refrigeration, Air Conditioning and Heat Pumps Technical Options Committee*. UNEP, Nairobi.

UNEP (2005). *Supplement to the IPCC/TEAP Report*. UNEP, Nairobi.

USEPA (2005). *Global Anthropogenic Non-CO_2 Greenhouse Gas Emissions: 1990 – 2020*. US Environmental Protection Agency, Washington.

Chapter 5

ACHRN (1999). *Hvac industry has seen 40 years of strong growth*. The Air Conditioning, Heating and Refrigerantion News 206(15):21-22.

Anderson J (2005). *Is STEK as good as reported?* Institute for European Environmental Policy IEEP, Brussels.

Australia (2009). *Exposure draft of the Carbon Pollution Reduction Scheme legislation.* http://www.climatechange.gov.au/emissionstrading/legislation/index.html (retrieved 30-3-2009).

Austria (2002). *Verordnung des Bundesministers für Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft über Verbote und Beschränkungen teilfluorierter und vollfluorierter Kohlenwasserstoffe sowie von Schwefelhexafluorid (HFKW-FKW-SF6-V) (Eng: Directive of the federal minister of agriculture, forestry, environment and water management on the ban and restriction of partly and fully fluorinated hydrocarbons and sulfurhexafluoride (HFC-PFC-SF6)).*BGBl. II Nr. 447/2002.

Bressers JThA (2004). *Implementing sustainable development: How to know what works, where, when and how,* in Governance for sustainanle development: the challenge of adapting form to function (Lafferty WM (ed)). Edward Elgar publishing, Cheltenham.

Bressers JThA and O'Toole LJ (1998). *The selection of Policy Instruments: a Network-based Perspective*. Journal of Public Policy 18(3):213-239. Cambridge University Press, Cambridge.

Caddy J (1997). *Hollow harmonisation? Closing the implementation gap in Central European environmental policy*. European Environment 7(3):73-79. John Wiley & Sons, Ltd.

Calm JM (2003). *Responsible responses to refrigerant regulation*. Engineered Systems 20(10):66-72.

Calm JM (2008). *The next generation of refrigerants - Historical review, considerations, and outlook*. International Journal of Refrigeration 31(7):1123-1133.

Dauvergne P (2008). *Refrigerating the Ozone Layer,* in The shadows of consumption - Consequences for the global environment (Dauvergne P (ed)). pg. 99-106. The MIT Press, Cambridge.

Dolowitz D and Marsh D (1996). *Who learns what from whom: A review of the policy transfer literature*. Political Studies 44(2):343-357. Blackwell Publishing Limited.

DuPont (2008). *Significant Environmental Benefits of New DuPont Refrigerant Recognized by Global Automotive OEMs.* http://vocuspr.vocus.com/vocuspr30/Newsroom/Query.aspx?SiteName=DupontNew&Entity=PRAsset&SF_PRAsset_PRAssetID_EQ=111534&XSL=PressRelease&Cache= (retrieved 23-2-2009).

EPEE (2001). *HFCs, refrigeration and air-conditioning: Minimising climate impact, maximising safety.* http://www.epeeglobal.org/English/HFCdocs/HFCs_and_Refrigeration_brochure.pdf (retrieved 23-2-2009).

EPEE (2005). *EU Climate Change Policy affecting Products has to be based on internal market rules.* http://www.epeeglobal.org/internet/docs/EU_Climate_Change_Policy_852.pdf (retrieved 25-2-2009).

European Commission (2001). *Annex I to the Final Report on the European Climate Change Programme Working Group Industry Work Item Fluorinated Gases - Position papers provided by stakeholders*. European Commission (DG Environment), Brussels.

European Commission (2003). *Proposal for a regulation of the European parliament and of the council on certain fluorinated greenhouse gases*.

European Commission (2006a). *Directive 2006/40 of the European Parliament and of the Council relating to emissions from air conditioning systems in motor vehicles and amending Council Directive 70/156/EEC*.2006/40.

European Commission (2006b). *Regulation (EC) No. 842/2006 of the European Parliament and of the Council of May 17th, 2006 on certain fluorinated greenhouse gases*.

Felder S and Rutherford TF (1993). *Unilateral CO2 Reductions and Carbon Leakage: The Consequences of International Trade in Oil and Basic Materials*. Journal of Environmental Economics and Management 25(2):162-176.

Fischer SK (1993). *Total equivalent warming impact: a measure of the global warming impact of CFC alternatives in refrigerating equipment*. International Journal of Refrigeration 16(6):423-428.

Fischer SK, Hughes PJ, Fairchild PD, Kusik CL, Dieckmann JT, McMahon EM, and Hobday N (1991). *Energy and Global Warming Impacts of CFC Alternative technologies*. AFEAS/ DOE, Washington DC/ Oak Ridge.

Grace IN, Datta D, and Tassou SA (2005). *Sensitivity of refrigeration system performance to charge levels and parameters for on-line leak detection*. Applied Thermal Engineering 25(4):557-566.

Guineé JB (2002). *Handbook on Life Cycle Assessment* . Kluwer Academic Publishers, Dordrecht.

Harnisch J and Gluckman R (2001). *Final report on the European climate change programme - working group industry - work item fluorinated gases. Prepared on behalf of the European Commission (DG ENV and DG ENTR)*. Ecofys/Enviros, Germany.

Hekkenberg M and Schoot Uiterkamp AJM (2007). *Exploring policy strategies for mitigating HFC emissions from refrigeration and air conditioning*. International Journal of Greenhouse Gas Control 1(3):298-308.

Hopkin M (2006). *Switching vet drug could save vultures.* http://www.nature.com/news/2006/060131/full/news060130-2.html (retrieved 25-2-2009).

IPCC (2006). *2006 IPCC Guidelines for national greenhouse gas inventories. Volume 3 - Industrial Processes and Product Use*. IGES, Japan.

IPCC (2007). *Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. IPCC, Geneva.

IPCC and TEAP (2005). *IPCC/TEAP Special Report on Safeguarding the Ozone Layer and the Global Climate System: Issues related to Hydrofluorocarbons and Perfluorocarbons.* Cambridge University Press, Cambridge and New York.

Johnson E (2004a). *HFC containment has already failed.* http://www.mipiggs.org/library/pdfs/hfccontainment.pdf. (retrieved 27-8-2009).

Johnson E (2004b). *New Directions: Fluorocarbon containment--reported results are exaggerated*. Atmospheric Environment 38(35):6079-6080.

Klok PJ (1991). *Een instrumententheorie voor milieubeleid (Eng: An instrumentation theory for environmental policy). (dissertation)* Faculteit der Bestuurskunde, Universiteit Twente, Enschede.

Maxwell J and Briscoe F (1997). *There's money in the air: The CFC ban and DuPont's regulatory strategy*. Business strategy and the Environment 6:276-286. John Wiley & Sons, Ltd.

McCulloch A (2009). *Evidence for improvements in containment of fluorinated hydrocarbons during use: an analysis of reported European emissions*. Environmental Science & Policy 12(2):149-156.

Oaks JL, Gilbert M, Virani MZ, Watson RT, Meteyer CU, Rideout BA, Shivaprasad HL, Ahmed S, Iqbal Chaudhry MJ, Arshad M, Mahmood S, Ali A, and Ahmed Khan A (2004). *Diclofenac residues as the cause of vulture population decline in Pakistan*. Nature 427(6975):630-633.

OECD (1995). *Environmental principes and concepts*. Organisation for Economic Co-operation and Development, Paris.

Pettigrew AM (1972). *Information Control as a Power Resource*. Sociology 6(2):187-204.

Schreuder Y (2009a). *The corporate greenhouse: climate change policy in a globalized world* . Zed Books, London / New York.

Schreuder Y (2009b). *The EU emissions trading scheme in the corporate greenhouse,* in The corporate greenhouse: climate change policy in a globalized world (Schreuder Y (ed)). Zed Books, London / New York.

Schwarz W (2001). *Emission of refrigerant R-134a from mobile air-conditioning systems*. Öko-Recherche, Frankfurt am Main.

Sekiya A and Misaki S (2000). *The potential of hydrofluoroethers to replace CFCs, HCFCs and PFCs*. Journal of Fluorine Chemistry 101(2):215-221.

SFT (2003). *Refusjonsordningen for HFK og PFK: Veileder (Eng: Refund regulation for HFC and PFC: tutorial).* http://www.sft.no/publikasjoner/luft/2064/ta2064.pdf. (retrieved 27-8-2009).

Tews K (2005). *The Diffusion of Environmental Policy Innovations: Cornerstones of an Analytical Framework*. European Environment 15:63-79. John Wiley and Sons, Ltd.

Tsai WT (2007). *Environmental risk assessment of hydrofluoropolyethers (HFPEs)*. Journal of Hazardous Materials 139(2):185-192.

UN (1987). *Montreal Protocol on Substances that Deplete the Ozone Layer*.

UN (1992a). *Rio declaration on environment and development*. UN, Rio de Janeiro.

UNEP (2002). *2002 Report of the Refrigeration, Air Conditioning and Heat Pumps Technical Options Committee*. UNEP, Nairobi.

UNFCCC (2009a). *Manufacturing and servicing of domestic refrigeration appliances using a low GWP refrigerant --- Version 1 (Methodology Approved by the CDM executive board).* http://cdm.unfccc.int/UserManagement/FileStorage/CDMWF_AM_9R0HVQOIO2AWALYMLDBNAUH4ONCUEM (retrieved 30-3-2009).

Van der Doelen FCJ (1993). *De gereedschapskist van de overheid. Een inventarisatie (Eng: The government's toolbox. An inventory),* in Beleidsinstrumenten bestuurskundig beschouwd (Eng: Policy instruments from a public administration perspective) (Bressers JThA, De Jong P, Klok P-J, and Korsten AFA (eds)). pg. 17-31. Van Gorcum & Comp B.V., Assen.

Verwoerd M (2001). *Nationaal onderzoek koudemiddelstromen 1999. Oorzaken van emissies (Eng: National study refrigerant flows 1999. Emission causes)*.R 2001/367. TNO MEP, Apeldoorn.

Willems S and Baumert K (2003). *Institutional capacity and climate actions*. Organisation for Economic Co-operation and Development/ International Energy Agency, Paris.

Wuebbles DJ and Calm JM (1997). *An Environmental Rationale for Retention of Endangered Chemicals*. Science 278(5340):1090-1091.

Chapter 6

Al-Zayer J and Al-Ibrahim A (1996). *Modelling the Impact of Temperature on Electricity Consumption in the Eastern Province of Saudi Arabia*. Journal of Forecasting 15:97-106. John Wiley & Sons, Ltd.

Amato A, Ruth M, Kirshen P, and Horwitz J (2005). *Regional Energy Demand Responses To Climate Change: Methodology And Application To The Commonwealth Of Massachusetts*. Climatic Change 71(1):175-201.

Bessec M and Fouquau J (2008). *The non-linear link between electricity consumption and temperature in Europe: A threshold panel approach*. Energy Economics 30(5):2705-2721.

Boonekamp PGM and Van Hilten O (1990). *Toekomstig verbruikspatroon van elektriciteit - mogelijke veranderingen en effecten (Eng: Future electricity consumption pattern - possible changes and effects)*.ECN-I--90-038. ECN, Petten.

CBS (2008). *Elektriciteit afzet binnenland 2003 (eng: Domestic electricity supply 2003).* http://statline.cbs.nl/StatWeb/. (retrieved 27-8-2009).

Crowley C and Joutz FL (2005). *Weather effects on electricity loads: modeling and forecasting*. USEPA, Washington.

Dijk D and Geerts M (1988). *Report on the Power System Simulation Model SCELEC*.IVEM report no. 23. Center for Energy and Environmental Sciences IVEM, Groningen.

ECN (2004). *Energie Verslag Nederland 2003 elektriciteits- en gasmarkt (Eng: Energy report Netherlands 2003 - electricity and gas market)*. ECN, Petten.

Eurostat (2008). *Monthly gross electricity consumption in Europe 1985-2006.* http://epp.eurostat.ec.europa.eu/portal/page/portal/eurostat/home. (retrieved 27-8-2009).

Franco G and Sanstad A (2008). *Climate change and electricity demand in California*. Climatic Change 87(0):139-151.

Hadley SW, Erickson III DJ, Luis Hernandez J, Broniak CT, and Blasing TJ (2006). *Responses of energy use to climate change: A climate modeling study*. Geophysical Research Letters 33(L17703).

Isaac M and Van Vuuren D (2009). *Modeling global residential sector energy demand for heating and air conditioning in the context of climate change*. Energy Policy 37(2):507-521.

KNMI (2008). *Daily weather data of the Netherlands.* http://www.knmi.nl/klimatologie/daggegevens/download.cgi?language=eng (retrieved 24-9-2008).

Mirasgedis S, Sarafidis Y, Georgopoulou E, Kotroni V, Lagouvardos K, and Lalas DP (2007). *Modeling framework for estimating impacts of climate change on electricity demand at regional level: Case of Greece*. Energy Conversion and Management 48(5):1737-1750.

Moral-Carcedo J and Vicéns-Otero J (2005). *Modelling the non-linear response of Spanish electricity demand to temperature variations*. Energy Economics 27(3):477-494.

Nobel F (1996). *Koude en zwoele nachten laten minimale belasting stijgen (Eng: Cold and sultry nights make minimal load rise)* . INspanning (April 1996):22-23.

Pardo A, Meneu V, and Valor E (2002). *Temperature and seasonality influences on Spanish electricity load*. Energy Economics 24(1):55-70.

Pennartz AMG (2005). *Onderzoek naar het elektrisch energieverbruik van koelinstallaties in Nederland - concept (Eng: Study of the electric energy consumption of cooling applications in the Netherlands)*. KWA bedrijfsadviseurs, Amersfoort.

Ruth M and Lin AC (2006). *Regional energy demand and adaptations to climate change: Methodology and application to the state of Maryland, USA*. Energy Policy 34(17):2820-2833.

Sailor DJ and Pavlova AA (2003). *Air conditioning market saturation and long-term response of residential cooling energy demand to climate change*. Energy 28(9):941-951.

Sailor DJ (2001). *Relating residential and commercial sector electricity loads to climate--evaluating state level sensitivities and vulnerabilities*. Energy 26(7):645-657.

Sailor DJ and Muñoz JR (1997). *Sensitivity of electricity and natural gas consumption to climate in the U.S.A.--Methodology and results for eight states*. Energy 22(10):987-998.

TenneT (2008). *Measured feed to the Dutch national grid.* http://www.tennet.org/english/operational_management/System_data_relating_processing/measured_feed.aspx. (retrieved 27-8-2009).

Valor E, Meneu V, and Caselles V (2001). *Daily Air Temperature and Electricity Load in Spain*. Journal of Applied Meteorology 40(8):1413-1421.

Van Arkel WG, Jeeninga H, Menkveld M, and Ruig RJ (1999). *Energieverbruik van gebouwgebonden energiefuncties in woningen en utiliteitsgebouwen (Eng: Energy use of energy functions in houses and buildings)*. ECN, Petten.

Wangpattarapong K, Maneewan S, Ketjoy N, and Rakwichian W (2008). *The impacts of climatic and economic factors on residential electricity consumption of Bangkok Metropolis*. Energy and Buildings 40(8):1419-1425.

Chapter 7

Aebischer B, Catenazzi G, Henderson G, and Jakob M (2007). *Impact of climate change on thermal comfort, heating and cooling energy demand in Europe*. ECEEE 2007 Summer Study: Saving energy - just do it! 859-870. ECEEE.

Al-Zayer J and Al-Ibrahim A (1996). *Modelling the Impact of Temperature on Electricity Consumption in the Eastern Province of Saudi Arabia*. Journal of Forecasting 15:97-106. John Wiley & Sons, Ltd.

Amato A, Ruth M, Kirshen P, and Horwitz J (2005). *Regional Energy Demand Responses To Climate Change: Methodology And Application To The Commonwealth Of Massachusetts*. Climatic Change 71(1):175-201.

Beccali M, Cellura M, Lo Brano V, and Marvuglia A (2008). *Short-term prediction of household electricity consumption: Assessing weather sensitivity in a Mediterranean area*. Renewable and Sustainable Energy Reviews 12(8):2040-2065. Elsevier.

Belzer DB, Scott MJ, and Sands RD (1996). *Climate Change Impacts on U.S. Commercial Building Energy Consumption: An Analysis Using Sample Survey Data*. Energy Sources 18:177-201.

Bessec M and Fouquau J (2008). *The non-linear link between electricity consumption and temperature in Europe: A threshold panel approach*. Energy Economics 30(5):2705-2721.

Cartalis C, Synodinou A, Proedrou M, Tsangrassoulis A, and Santamouris M (2001). *Modifications in energy demand in urban areas as a result of climate changes: an assessment for the southeast Mediterranean region*. Energy Conversion and Management 42(14):1647-1656.

Franco G and Sanstad A (2008). *Climate change and electricity demand in California*. Climatic Change 87(0):139-151.

Hadley SW, Erickson III DJ, Luis Hernandez J, Broniak CT, and Blasing TJ (2006). *Responses of energy use to climate change: A climate modeling study*. Geophysical Research Letters 33(L17703).

Hekkenberg M, Benders RMJ, Moll HC, and Schoot Uiterkamp AJM (2009). *Indications for a changing electricity demand pattern: The temperature dependence of electricity demand in the Netherlands*. Energy Policy 37(4):1542-1551.

Henley A and Peirson J (1997). *Non-linearities in electricity demand and temperature: parametric versus non-parametric methods*. Oxford bulletin of economics and statistics 59(1):149-162. Blackwell Publishers Ltd., Oxford.

Isaac M and Van Vuuren D (2009). *Modeling global residential sector energy demand for heating and air conditioning in the context of climate change*. Energy Policy 37(2):507-521.

Le Comte DM and Warren HE (1981). *Modeling the Impact of Summer Temperatures on National Electricity Consumption*. Journal of Applied Meteorology 20(12):1415-1419.

McKittrick DA, Hacia H, Vitale CS, and Arkin MA (1991). *Climates of the World*. National Oceanic and Atmospheric Administration, Asheville.

Mirasgedis S, Sarafidis Y, Georgopoulou E, Kotroni V, Lagouvardos K, and Lalas DP (2007). *Modeling framework for estimating impacts of climate change on electricity demand at regional level: Case of Greece*. Energy Conversion and Management 48(5):1737-1750.

Moral-Carcedo J and Vicéns-Otero J (2005). *Modelling the non-linear response of Spanish electricity demand to temperature variations*. Energy Economics 27(3):477-494.

Pardo A, Meneu V, and Valor E (2002). *Temperature and seasonality influences on Spanish electricity load*. Energy Economics 24(1):55-70.

Parkboom S and Harrison G.P (2008). *Analyzing the Impact of Climate Change on Future Electricity Demand in Thailand*. IEEE Transactions on Power Systems 23(3):1441-1448. IEEE.

Rosenthal DH and Gruenspecht HK (1995). *Effects of global warming on energy use for space heating and cooling the the United States*. Energy Journal 16(2):77-96.

Sailor DJ and Pavlova AA (2003). *Air conditioning market saturation and long-term response of residential cooling energy demand to climate change*. Energy 28(9):941-951.

Sailor DJ (2001). *Relating residential and commercial sector electricity loads to climate--evaluating state level sensitivities and vulnerabilities*. Energy 26(7):645-657.

Sailor DJ and Muñoz JR (1997). *Sensitivity of electricity and natural gas consumption to climate in the U.S.A.--Methodology and results for eight states*. Energy 22(10):987-998.

Scott MJ, Wrench LE, and Hadley DL (1994). *Effects of Climate Change on Commercial Building Energy Demand*. Energy Sources 16:317-332.

Thatcher MJ (2007). *Modelling changes to electricity demand load duration curves as a consequence of predicted climate change for Australia*. Energy 32(9):1647-1659.

Valor E, Meneu V, and Caselles V (2001). *Daily Air Temperature and Electricity Load in Spain*. Journal of Applied Meteorology 40(8):1413-1421.

Wilbanks TJ, Bhatt V, Bilello DE, Bull SR, Ekmann J, Horak WC, Huang YJ, Levine MD, Sale MJ, Schmalzer DK, and Scott MJ (2007). *Effects of climate change on energy production and use in the United States - final report of the synthesis and assessment product 4.5*. US Climate Change Science Programme, Washington.

LIST OF ABBREVIATIONS AND ACRONYMS

AFEAS	alternative fluorocarbons environmental acceptability study
AM0071	approved methodology nr 71 of the CDM
ARAP	the alliance for responsible atmospheric policy
BaU	business as usual
C&C	command and control
CBS	statistics Netherlands
CDD	cooling degree day
CDM	clean development mechanism
CFC	chlorofluorocarbon
CH4	methane
CO2	carbondioxide
CO2-eq	carbondioxide equivalent
COM	commercial refrigeration
con	containment
COP	coefficient of performance
COP	conference of the parties
DDT	dichlorodiphenyltrichloroethane
DEV	developing country
ECN	energy research centre of the Netherlands
EoL	end of life
ERI	energy research institute
EU	European Union
EU-ETS	European Union Greenhouse Gas Emission Trading System
F-gas	fluorinated gas
GAINS	greenhouse gas and air pollution interactions and synergies
GEF	global environmental facility
GHG	greenhouse gas
GNP	gross national product
Gt	gigaton
GWP	global warming potential
HC	hydrocarbon

HCFC	hydrochlorofluorocarbon
HDD	heating degree day
HFC	hydrofluorocarbon
HFPE	hydrofluoropolyether
HG	high growth
HS	high substitution
IEA	international energy agency
IIASA	international institute for applied systems analysis
IND	industrial refrigeration
IND	industrialized country
IPCC	intergovernmental panel on climate change
IVEM	center for energy and environmental sciences
KNMI	royal dutch meteorological institute
kt	kiloton
LCA	life cycle assessment
LS	low substitution
LUC	land use change
MAC	mobile air conditioning
MG	medium growth
Mt	megaton
MW	megawatt
N20	nitrous oxide
NASA	national aeronautics and space administration
NH3	ammonia
ODP	ozone depleting potential
ODS	ozone depleting substance
OECD	organization for economic cooperation and development
PFC	perfluorocarbon
po	phase out
ppm	parts per million
R&D	research and development
R+AC	refrigeration and air conditioning
REF	refrigeration
SAC	stationary air conditioning
SEEP	socio-economic environment policy
SEP	cooperating energy producers (samenwerkende energie producenten)
SF6	sulfurhexafluoride
STEK	stichting emissiepreventie koudetechniek (foundation emissionprevention cryogenics)
TDP	temperature dependence pattern
TEAP	technology & economic assessment panel
TEWI	total equivalent warming impact
TRA	transport refrigeration
TSO	transport system operator
TWh	terawatthour

UBA	umweltbundesamt
UN	United Nations
UNEP	United Nations environmental programme
UNFCCC	United Nations framework convention on climate change
USA	United States of America
USEPA	United States environmental protection agency
WMO	world meteorological organization
WRI	world resources institute
WTO	world trade organization
YSSP	young scientists research programme

CURRICULUM VITAE AND PUBLICATION LIST

Curriculum Vitae

Michiel Hekkenberg was born in Buurmalsen, the Netherlands, on 2 January 1978. In 2002 he received a M.Sc. degree at the University of Groningen, graduating in Biology with a specialization in Energy and Environmental Sciences. His M.Sc. thesis dealt with the position of stakeholders towards various technologies for sustainable transport. From 2002 through 2004 he pursued various temporary jobs. From 2004 through 2009 he worked as a Ph.D. candidate at the Center for Energy and Environmental Sciences IVEM of the University of Groningen. As part of this work, he participated in the Young Scientists Summer Programme (YSSP) at the International Institute for Applied Systems Analysis (IIASA) in Laxenburg, Austria in 2007. He graduated in 2009 on the interaction between local cooling demand, climate change and international policy strategies. Currently, he works as a researcher in the National Emission Strategies group of the Policy Studies unit of the Energy Research Centre of the Netherlands (ECN).

Publications

Scientific articles

Hekkenberg, Moll and Schoot Uiterkamp (2009). *Dynamic temperature dependence patterns in future energy demand models in the context of climate change.* Energy (*in press*). doi:10.1016/j.energy.2009.07.037

Hekkenberg, Benders, Moll and Schoot Uiterkamp (2009). *Indications for a changing electricity demand pattern: the temperature dependence of electricity demand in the Netherlands.* Energy Policy 37:1542-1551. doi:10.1016/j.enpol.2008.12.30

Hekkenberg and Schoot Uiterkamp (2007). *Exploring policy strategies for mitigating HFC emissions from refrigeration and air conditioning.* International Journal of Greenhouse Gas Control 1(3):298-308. doi:10.1016/S1750-5836(07)00030-8

Hekkenberg, Moll and Schoot Uiterkamp (submitted). *Refrigerant emissions from a global governance perspective.*

Reports

Hekkenberg (2007). *Baseline F-gas emission projection for China 2000-2030 for GAINS Asia*, (report of Young Scientists Summer Programme research project at the International Institute for Applied Systems Analysis IIASA), IIASA, Laxenburg.

Hekkenberg (2002). *De rol van actoren bij introductie van verschillende nieuwe technologieketens in het verkeer en vervoer* (Eng: The position of stakeholders towards various technologies for sustainable transport), IVEM-master thesis 138, University of Groningen, Groningen, Nederland (master thesis).

Hekkenberg (2001). *Energiekosten wegonderhoud aan de provinciale wegen in Drenthe* (Eng: Energy costs of road maintenance of provincial roads in Drenthe), IVEM-learning thesis 130, University of Groningen, Groningen Nederland.

Presentations

Hekkenberg and Schoot Uiterkamp (2009). *Comparing incentive for stakeholder cooperation in the Montreal and the Kyoto Protocol*. Climate Change International Scientific Congress. Copenhagen, Denmark.

Hekkenberg (2008). *Improving stakeholder cooperation in post Kyoto climate policy*. *SENSE-EPCEM symposium*. Wageningen, the Netherlands.

Hekkenberg (2008). *Involving developing countries in Kyoto*. Young Scientists Winter Symposium. Laxenburg, Austria.

Hekkenberg, J. Potting, D. de Jager and A.J.M. Schoot Uiterkamp (2005). *Assessing cooling applications with a simplified life cycle approach in the context of the Montreal and Kyoto protocols*. Fourth International Symposium on Non-CO_2 Greenhouse Gases: Science, Control, Policy and Implementation. Utrecht, the Netherlands.